A BINAURAL SINGLE OBJECT SENSOR AS A MOBILITY AID FOR THE BLIND

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by

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ABSTRACT

This thesis describes a feasibility study of a binaural single object sensor as a mobility aid for the blind.

Firstly, arguments are advanced for a mobility aid presenting the spatial information in a manner similar to the natural echo-location phenomenon that is experienced by many blind people. It is further argued that the aid should preferably detect only the nearest object in its illuminating field.

A pulsed single object sensor (SOS) is then designed with rectified echo pulses as the auditory stimulus. Using the sing-around principle as the mechanism for switching the transmitting pulses, the distance to an object is coded as inversely proportional to the rate of repetition of the audio pulses. Auditory lateralization with an experimental model of the SOS shows that interaural amplitude difference is the most suitable lateralization mechanism.

The presentation of dichotic sounds such that they provide the "out-of-the-head" sensation is also studied. This involves theoretical and experimental examination of the role of pinna in auditory localization. It was found that the pinna is the most important factor in externalizing a sound image. An analogue cross correlator with spatial resolution in the order of 3-4mm was constructed to measure the pinna transfer function. It was found that, while the pinna produces 3 groups of distinct delayed replicas of the original sound, the variation of the amplitude of the replicas with direction was too complex to be realized in a portable aid. This, together with a comparison of locomotion

control under headphones and free-field listening condition, tends to justify the use of lateralization as the mechanism to determine the direction to an object in the SOS.

Laboratory studies of spatial perception with the aid were carried out, with particular reference to the perception of change in the distance to an object, the use of loudness as an extra distance cue, the object recognition capability, and the control of locomotion in various locomotive tasks. Locomotion performances were also compared with Kay's Binaural Sensory Aid and unaided performances.

The problems involved in evaluating a sensory aid are discussed, and an analysis of mobility activities is provided. The possible usefulness of the aid in these activities is indicated.

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CHAPTER 1

INTRODUCTION

1.1 BLIND POPULATION AND MOBILITY OF THE BLIND

Blindness is one of the most disabling impairments to afflict mankind. Estimates of the number of the blind vary widely from one country to another, depending on the definition of blindness. In general, the incidence of blindness is lowest in European countries, being about 20 per 10,000, and highest in West African countries, being 100 or more per 10,000 (Roger, 1958; Josephson, 1965; WHO, 1966; Golstein, 1968; Gray and Todd, 1968; Goldish, 1972; RNZFB, 1977). The total number of blind persons in the world is estimated to be between 10 and 14 millions (Wilson, 1965). Some may have a certain amount of residual vision and may be able to travel unguided, but a considerable proportion is totally blind or have only light perception. (16.3% in U.S.A.; 24% in England and Wales). For these people, one of the most severe sufferings is the lack of independent mobility. *"The need to travel or move freely is one of the obstacles presented by the handicap of blindness, and the inability to do so often becomes the most formidable limitation".* (Miller 1962).

Even for people with some residual vision, independent travelling is not easy. Only the young and the healthy blind have the motivation to travel (Josephson, 1965) and few do well (Samuel et al; 1960).

The lack of travel commitment by the blind could be attributed to the lack of readily effective means or devices to present to the blind pedestrians the spatial information which is normally available to sighted pedestrians.

This thesis studies the feasibility of an ultrasonic head-mounted "echo-ranging" type system as a simple-to-use mobility aid. It is argued that such an aid should provide to a user information about only the nearest object. Also, the information should be presented in such a way that it enhances the spatial perception of the sensory modality chosen to replace vision. A portable binaural mobility aid was designed, with lateralization as the mechanism for determining the direction to an object and the "Sing - Around" technique (Greenspan and Tschiegg, 1957) for determining the distance to the object. Auditory localization, especially the transfer function of the pinna, were also also studied in a serious but unsuccessful attempt to modify the auditory stimulus of the aid in order to enhance the natural echo-location ability of the user.

Psychoacoustical and locomotion control experiments were conducted to gain some insight into the spatial perception with the auditory display of the aid, and to compare locomotion performances, in a controlled environment, with a well established aid providing more detailed spatial information.

Mobility activities in real environments are also analysed to provide a basis for an objective evaluation of sensory aids. The potential usefulness of the SOS in each of these activities is estimated to serve as a starting point for future evaluation programs.

1.2 THESIS ORGANIZATION

Chapter 2 reviews current thoughts on the question of the information necessary for mobility and the requirements of a mobility aid. A survey of existing mobility aids is presented, together with their potential for improving mobility of the blind. Arguments are then put forward to show that a simple-to-use mobility aid providing information about only the nearest object could benefit a large proportion of the blind population. Accordingly, the aid is called the Single Object Sensor (SOS).

Chapter 3 is concerned with the coding of the spatial information in the Single Object Sensor. A pulse system was chosen to provide a distance coding such that the rate of repetition of the echoes is inversely proportional to the distance to an object. Experiments were carried out to study auditory lateralization with an experimental model of the SOS. Lateralization by Interaural Amplitude Difference (IAD), Interaural Time Difference (ITD) and a combination of IAD and ITD were examined.

Chapter 4 is devoted to the engineering design of the sensor. The choice of the aid beamwidth, transmitting frequency and the size of the minimum detectable object are presented. The designs of some of the system circuitry are described.

Chapter 5 is concerned with the possible improvement of the auditory spatial perception when lateralization is replaced by localization. Localization was shown to be most affected by the modification of sound waves by the outer ears or the pinnae. A cross-correlator was constructed to measure the pinna transfer function in view of possible incorporation of the localization mechanism into the auditory display of the aid. However, it was shown that the transfer function cannot be easily reproduced electronically. This, in combination with results from an experiment comparing locomotor performances using lateralization and localization, indicates that for a portable mobility aid, lateralization is a most suitable choice.

Spatial perception with the aid in a controlled environment is studied in Chapter 6. With the auditory stimulus from a simple object approximated by periodic pulses, the perception of relative change in the distance of an object was studied by examining the (equal interval) change in pitch of the periodic pulses. Equal loudness contours of periodic pulses are also determined in an attempt to use loudness as an additional distance cue. Control of locomotion in a variety of tasks was then studied. Comparison with a well established binaural mobility aid (the Binaural Sensory Aid) and unaided performances are also provided.

The possible usefulness of the aid in the real environment is discussed in Chapter 7. Firstly the object recognition capability of the aid is studied. The problems involved in evaluating a sensory aid are then examined and an evaluating method involving an analysis of mobility activities, is proposed. The potential usefulness of the aid in these activities is then estimated to serve as a basis for future evaluation program.

A summary of results and suggested areas for further research are presented in Chapter 8.

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CHAPTER 2

MOBILITY AIDS FOR THE BLIND AND THE PRINCIPAL FEATURES OF A SIMPLE-TO-USE AID

2.1 INTRODUCTION

The necessity of a sensory aid to improve the mobility of the blind has been widely recognised. A mobility aid should convey to a blind user information about his surroundings in sufficient detail to enable him to travel safely. As such, it should perform three basic functions: sensing the environment, processing, and displaying the gathered information (Nye and Bliss, 1970). But, as will be seen later, widely different views are held as to how a mobility aid should perform these functions.

The diversification of opinions is probably due to the lack of basic knowledge about mobility and about the problem of interfacing a sensory subtitution system to a human operator: It is not clear as to what constitutes the necessary information for mobility, nor as to the psychophysiological advantages of different types of sensory modalities that can be used to replace vision (Clowes, 1965; Nye, 1971). The widely differnt opinions are reflected in the number of devices (over 20) built in the last quarter of the century.

This chapter reviews the current thoughts on blind mobility, starting with the definition of mobility and the information required for mobility. A survey of the current mobility aids is then presented. From the discussion of mobility with these aids, it is argued here that a simple-to-use aid could benefit a large proportion of the blind population. The principle features of such an aid are discussed in the final section of this chapter.

2.2 MOBILITY: A DEFINITION

Mobility has been defined by Psathas (1796) as "*the movement of an embodied person with total bodily movement which involves a change in spatial location accomplished in an upright position under one's own power*". This definition concisely describes the physical movement or the locomotion function of a pedestrian. But is is sharply different from that advanced by Kay (1974) who defined mobility as "*walking in public places with a physical ease and mental confidence which allows one to blend naturally with one's fellow pedestrians*". In Kay's definition, a new aspect of mobility is implicitly introduced: orientation. Kay implies that the act of walking in public places indicates that a pedestrian can orientate himself toward his destination; otherwise he would halt and seek help. In this respect, Kay's definition is similar to those forwarded by Foulke (1971) and Armstrong (1973) and seems to reflect the view shared by many mobility researchers that "mobility is a combination of locomotion and orientation".

2.3 REQUIREMENTS OF A MOBILITY AID

Many views have been put forward as to the requirements of a mobility aid. The following section reviews the most recent thoughts.

Russell (1965) argued that a mobility aid should offer advanced warning of collision, freedom from strain, and minimum interference with the natural cues used by the remaining senses. He mainted that this condition can be achieved by pre-processing the information from the environment and presenting the user with the simple fact that the path in front of him is clear or not. On the other hand, Dupress (1965) thought that a mobility aid should provide not only a "no object condition" for the next step but also information about a safe platform on which to step, and information for successful orientation and navigation. Dupress' ideas seem to receive increasing acceptance by other researchers in the field. Eftman (1968) believed that mobility aids should provide sufficient information about the environment surrounding a blind pedestrian so as to enable him to avoid obstacles and to navigate. White (1970) thought that a mobility aid which produces only the information about the position of the objects may not be sufficient for mobility. He argued that the ability to recognise objects is an important feature to enable a blind person to reconstruct and hence to perceive his surrounding. Carrying the idea further, Foulke (1971) argued that the information presented to the blind must represent more of the pedestrian's environment than the path he intended to follow, so that a departure from the path will not present him with information that is meaningless to him.

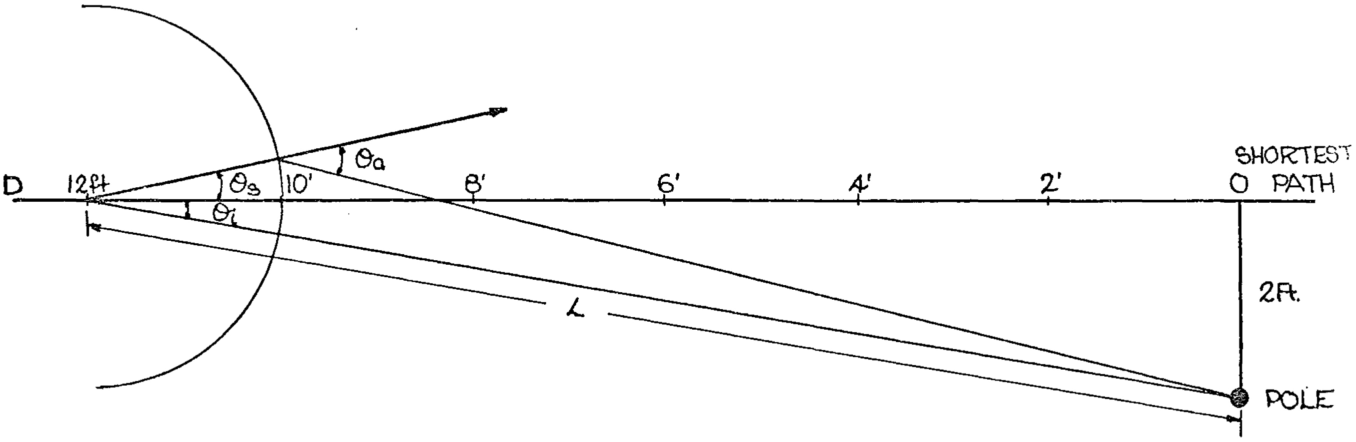
Using a different approach, Leonard (1971) supplied a list of the categories of information provided by vision for the purpose of sighted mobility, which comprised:
object detector including obstacle and landmarks;
orientation for near and far field;
terrain change;
posture.

He speculated that the information provided by an aid to the blind's mobility should have the same capabilities.

Emphasising on the psychological aspect of mobility, Armstrong (1972) argued that a mobility aid should enable a blind person to travel safely, efficiently (shortest route in shortest time), and without undue psychological stress.

Gibson (1958), while not specifically concerned about mobility aids, produced an interesting theory of visually-controlled locomotion. He postulated that locomotion toward an intended object involves keeping the centre of flow of the optic array (reflected from the illuminated environment) as close as possible to the object. As with other mobility hypothesis, the importance of the centre of flow of the optic array in locomotion has not been conclusively established (Warren, 1976) nor refuted (Johnston, White, and Cumming, 1973).

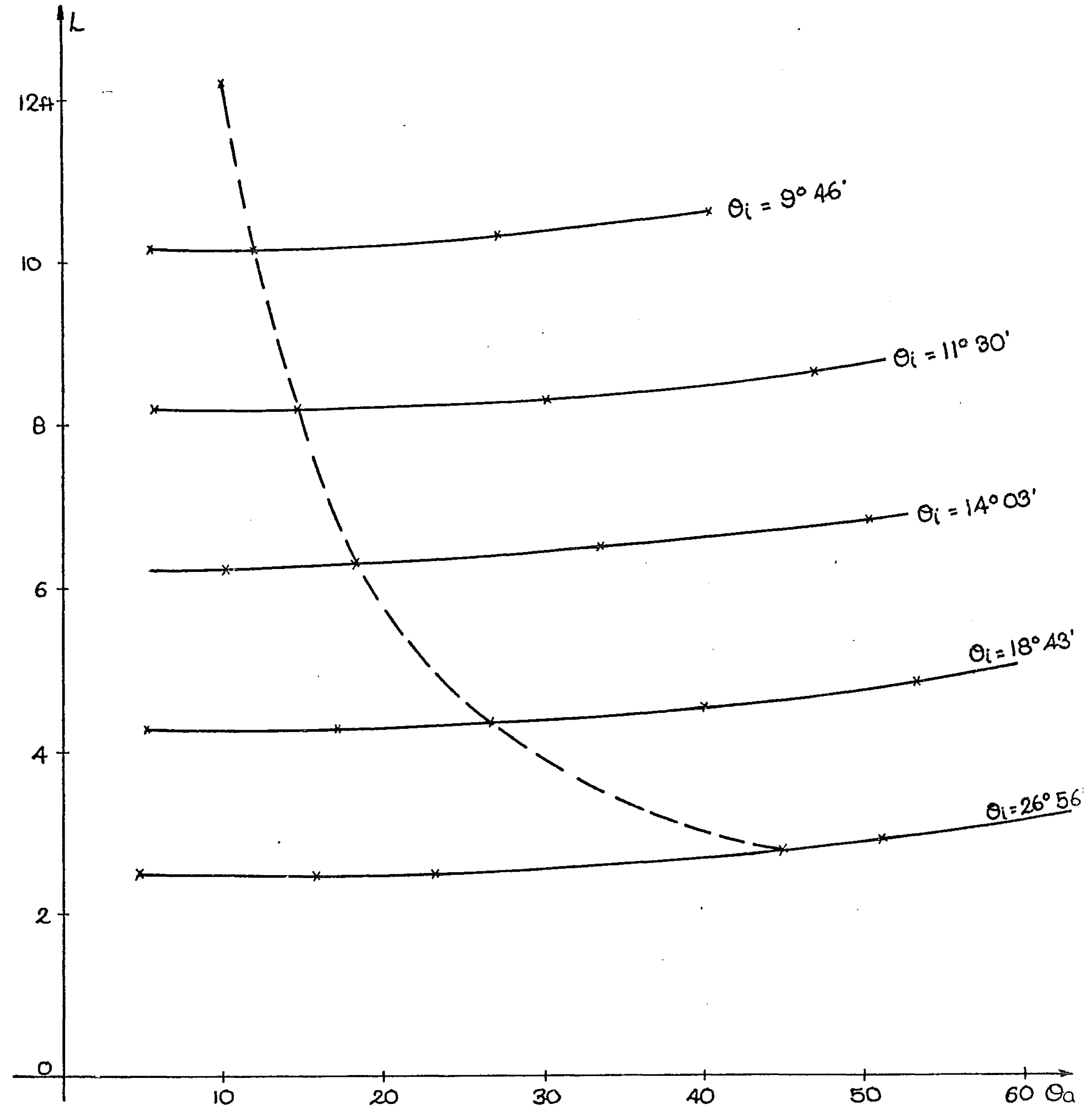
In a more practical apprach, Kay (1974) separated the spatial information from an element of space into distance and direction information. Using the task of walking past a pole at a distance as an example (fig. 2.1), Kay showed that (fig. 2.2), given the initial direction of the pole (Θ_i) the pole's direction after a step is taken (Θ_a) (in a particular direction (Θ_s)) specifically determines the distance of the pole. But since the angles and the rates of change can only be roughly determined by the senses and careful calculation must be performed by the central nervous system to produce the appropriate movement, Kay argued that a smooth control of the body in performing the task is not possible. Similarly, when only distance information is available, the directions of the pole can be determined correctly if the initial pole distance (D_i) and the fractional change in distance are available (Fig. 2.3)



WALKING PAST A POLE AT 2Ft DISTANCE.

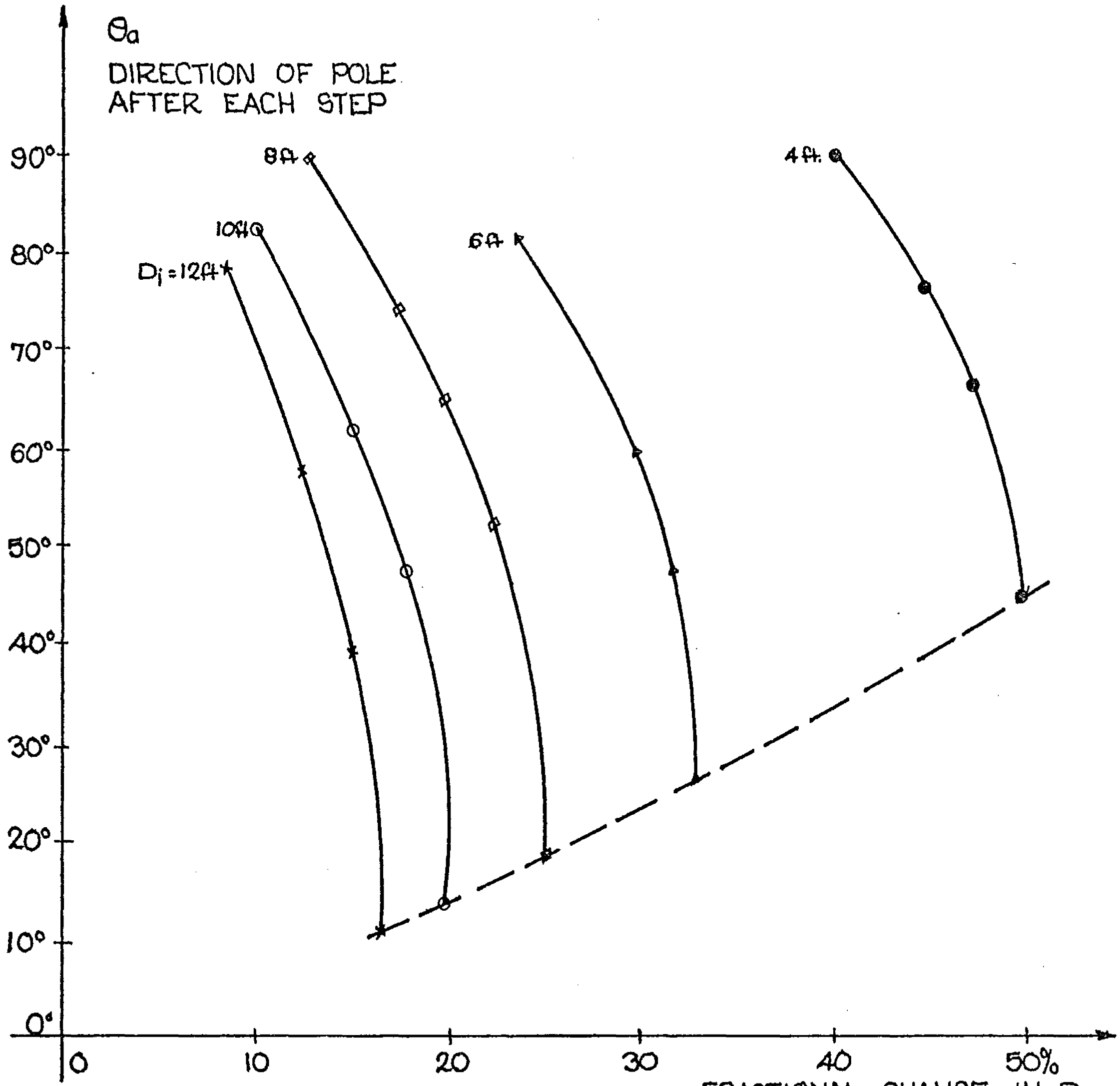
θ_i = INITIAL DIRECTION OF POLE AT BEGINNING OF EACH STEP.
θ_a = DIRECTION OF POLE AFTER EACH STEP θ_s = DIRECTION OF MOVEMENT
L = DISTANCE TO THE POLE 2Ft = STEP LENGTH

FIG. 2.1



WALKING PAST A POLE AT 2Ft DISTANCE WITH ANGLE INFORMATION ONLY.
— — — REPRESENTS THE STRATEGY REQUIRED TO WALK ON THE SHORTEST PATH

FIG. 2.2



WALKING PAST A POLE AT 2ft WITH DISTANCE INFORMATION ONLY.

D_i = INITIAL DISTANCE AT THE BEGINING OF EACH STEP

— — — REPRESENTS STRATEGY REQUIRED TO WALK ON THE SHORTEST PATH.

FIG. 2.3

Again, Kay argued that since considerable thought must be given to a strategy of movement for completing the task, smooth and graceful motion is not possible. However, when distance and direction information are available, Kay maintained that by combining the variables, finer control of movement is possible. Kay further argued that, since the execution time of the above task is much shorter than the time required to compute the related data, a newly-presented situation may merely activate a percept closely related to the situation. A pedestrian may just then operate on the read-out of spatial patterns from the spatial memory. As a consequence, a sensory aid should produce learnable patterns so that a new spatial percept can be established.

The study of veering of the blind by Cratty and his colleagues (Cratty and Williams, 1966; Cratty, 1967; Harris, 1967), while not specifically indicating the requirements of a mobility aid, pointed out another aspect of mobility without vision: The tendency to veer. They found that on the average, a blind person veers 37° per 100 ft.

Most of the opinions cited above are of a speculative nature rather than based on hard evidences. In fact, it is only very recently that efforts have been concentrated on researches into the basics of mobility, noticeably mobility researches at the University of Nottingham Blind Mobility Research Unit (Armstrong, 1973; Delafield, 1974), the Perceptual Alternatives Laboratories (Foulke, 1975), and the Canterbury Mobility Laboratory (Brabyn, 1978). The results from these researches have not yet had a far-reaching impact on the question of the requirements of a mobility aid.

2.4 MOBILITY AIDS: THE STATE OF THE ART

Sensory aids for the blind have a long history. Apart from sighted companions, the canes (long and short) are the earliest mobility aids recorded. After the canes, the training of the guide dog is one of the serious attempts to improve mobility of the blind. Then, with the advancement of modern technology, a new generation of electronic mobility aids emerged. Because of the widely-different opinions on the requirements of a mobility aid, these aids have been built, basing on a variety of principles, using an assorted number of techniques such as radar, sonar, lasers to explore the environment, and employing a number of sensory modalities such as hearing, tactile to convey the spatial information. Most of these aids were designed to be used in conjunction with the long cane. Many of them were never actually developed beyond the experimental stage. Only a small number of them reached the evaluation stage and an even smaller number was well-accepted. Since the development of mobility aids has been well-documented (for example, see Shrager and Susskind, 1964; Bliss, 1966; Mims, 1974), the following section reviews only those devices well-accepted as mobility aids or in the later stages of evaluation.

The Long Cane

The Long Cane is the most widely-used mobility aid (30% of the blind population; OSTI, 1971). Although the cane has been reportedly used as a mobility aid as far back as the time of the ancient prophet Teresias and the Goddess Clarido (Levy, 1949) it was not until after World War II that efforts were made to develop a standard technique for the Long Cane, which is widely known as the Hoover cane technique (Hoover, 1950).

Basically, the cane is used as a bumper to protect the user from colliding with objects. But, with proper training, the cane can be used to provide information about the area into which the next step is to be taken, such as the nature of the ground, the texture and the gradient of the ground surface.

The range of exploration by the Long Cane is limited by its length; the maximum length is about 1.6m.

The Guide Dog

Dogs have been known to be trained as guides since 1819, but it was not until the German Shepherd Dog Society established a training school early this century that the Guide Dog was seen as a possible mobility aid for the blind. Mobility with a well-trained Guide Dog is inconspicuous and can be relaxing in a familiar environment. In an unfamiliar environment, the blind pedestrian need to have a cognitive map of the intended route. He then can rely on his dog to detect obstacles and to keep him from excessive veering along the route.

It is estimated that 2% to 4% of the total blind population can benefit from a Guide Dog (Peel, 1975).

The Long Cane and the Guide Dog are often referred to as primary aids.

The Pathsounder Travel Aid

The Pathsounder, developed by Russel (1965, 1969) is a small battery-operated sonar to be used as a travel aid in conjunction with the Long Cane.

The device is worn on the chest by means of a neck strap and produces an audible warning when there is an object within 2 metres ahead of the user, in the region roughly from his waist to the top of his head.

The audible warning is in the form of a buzzing sound which changes into a high-pitched beeping sound when the object comes within 0.8m.

The device is thought to be useful in providing:

1. Early warning of objects in the travel path, including pedestrians;
2. Protection against overhanging objects which cannot be detected by the Long Cane, such as the tail gate of an unloading truck.

The Bionic Instruments C-4 Laser Cane

The Laser Cane, in the form of a long cane, contains three infra-red light emitters which look simultaneously down, straight ahead, and upward, (Benjamin, 1971). It is to be used independently from other primary aids.

The downward channel produces a low-pitched warning sound if there is any drop-off larger than about 0.25in, approximately two paces in front of the user.

The straight ahead channel detects objects within about 3m in front of the user and activates a stimulator contacting the index finger of the user.

The upward channel detects objects appearing at head height and directly above the cane tip. It produces a high-pitched warning tone.

The infra-red beams are made very narrow (about 0.05m wide at 3m range) so that objects may be located with considerable precision by suitable scanning.

The Laser Cane was found to be most effective in two principle situations (Nye, 1973):

1. In moderately dense traffic along familiar routes.
2. In unfamiliar urban areas with low traffic density.

It was found that the performance of above average Long Cane travellers is only marginally improved when the Laser Cane is used istead of the Long Cane.

The Sonic Torch

The Sonic Torch or Kay Sonic Aid (Kay, 1962), is a hand-held sonar which transmits bursts of Frequency-Modulated (FM) ultra-sonic signals. The received signals after demodulation are presented to the user in the form of audible sounds. The object distance is coded in the pitch of the audible signal. The pitch changes continuously and proportionally with distance with the highest pitch for objects at the maximum distance (about 4m). The characteristic of the sound, for example soft or harsh, provides information about the texture of the objects.

The device, by proper scanning, can replace the Long Cane to detect and sense objects in front of the user as well as any abrupt change in the gradient of the ground surface. From the information provided by the display, object recognition is often possible (Sharp, undated).

The Binaural Sensory Aid (BSA)

Also known as the Sonic Guide, or the Sonic Glasses, the BSA (Kay, 1966) is a head-mounted stereo version of the Sonic Torch. The object distance is coded in the pitch of the audible signals and the object azimuth angle is coded in the interaural amplitude difference between the sound in the left and right channels of the auditory display. Thus, without head scanning, the relative position of objects within the device beam can be perceived. The BSA is to be used with the Long Cane or the Guide Dog and is found to improve the mobility of Long Canse users, as well as providing them with more detailed information about their immediate environment (Thorton, undated; Airasian, 1973).

Apart from the above mobility aids, several devices and means are being investigated as possible aids for the blind. For example, the Nottingham Obstacle Detector (Armstrong, 1973), the Swedish Laser Cane (Jansson and Schenkman, 1977), the Mowatt Sensor (Pressey, 1977), the Optical-to-Tactile Environment Sensor (Bliss, 1971), the Tactile Sensory Vision Replacement System (Collins and Madley, 1974), and the Electro-cortical Visual Prosthesis Technique (Vaughan and Schimmel, 1970; Cozman, 1975). These are still being evaluated, and their potential in improving the mobility of the blind has not yet been well established.

2.5 EFFECTS OF EXISTING AIDS ON MOBILITY OF THE BLIND

The value of the Guide Dog and the Long Cane in mobility is undeniable. They change the mobility status of a number of blind people from home-bound to independent travellers.

Of the two aids, the Guide Dog seems to be a more reliable guidance system in familiar environments. The Guide Dog is trained to obey his master's command only when it is safe to do so. Furthermore, the ability of a Guide Dog improves with experience. However, a considerable amount of attention must be paid to the dog: to accept him as a part of the family, to cater for his needs, and to exercise him regularly. These requirements can be of a great burden for some blind people; therefore, not all blind people accept a Guide Dog as their mobility aid.

The Long Cane, on the other hand, requires only a minimum amount of maintenance. However, since it can only provide limited information about objects within the region of the next step of the user; an abrupt half, rather than graceful avoidance of objects, is often a characteristic of Long Cane users. This causes considerable stress to the new users who normally anticipate possible collision at almost every step. Probably, as a consequence, mobility performance has been found to deteriorate with time (Nye, 1973; p.14). Furthermore, since the Long Cane, for most of the time, can only indicate the presence or absence of objects, discrimination of objects and recognition of landmarks are very poor.

It was often thought that the mobility of a Long Cane user could be improved with the use of a mobility aid capable of providing long-range information about the presence of obstacles on the user's path (Russell, 1965). Obstacle avoidance can then be executed in a graceful manner and stress in the user can be reduced. A number of devices has been designed following that principle. They are often referred to as Clear Path Indicator (Kay, 1966). They enable a user to navigate safely (locomotion), but due to the lack of detailed information about the shape and size of the detected objects, recognition of objects with the aid, and hence orientation toward landmarks, are often difficult. As a consequence, they have not yet found wide acceptance. The Russell's Path Sounder and the Laser Cane are typical examples.

As knowledge on blind mobility gradually built up, the concept of a clear path indicator with a simple yes/no output as a mobility aid has been challenged (White, 1970; Fourke, 1971). While the user's stress may have been reduced by providing him with long-range information, the mobility performance has not been improved (Nye, 1973). More detailed information about objects in the environment, so that object recognition and pattern generation are possible, was thought to be necessary for mobility aid to lift the mobility performance above that of the Long Cane users. Such aids are often referred to as Environment Sensors. The Sonic Torch and the BSA belong to this group. Of these aids, only the usefulness of the BSA has been well evaluated in a considerable large scale evaluation programme (Ward, 1972; Murphy, Johnson, Stealey, and Ima, 1973; Kay, 1973; Airasian, 1973). The BSA has been shown to greatly improve the object recognition capability of a blind thanks to the richness of information contained in its display. Mobility performance has also been shown to improve (Airasian, 1973).

However, since the information contained in the display of the BSA is very rich and complex, it can be difficult for a blind person to learn to effectively use the information (Armstrong, 1973; P.10). Consequently, it is thought that the BSA may benefit only a very small proportion of the blind population (probably 1%; Murphy et al., 1973; p.27). A simpler-to-use mobility aid has been argued to be more beneficial to a larger proportion of the blind population (Armstrong, 1973; p.2).

A simpler-to-use auditory mobility aid is the theme of this thesis; the philosophy behind the main concepts of the aid is presented in the next section.

2.6 A SIMPLE-TO USE MOBILITY AID

The limited success, so far, of the electronics aid can be due to the failure to take into account the psychological effects of using a new sensory modality to substitute for vision, and the wrong assumption that the various senses of man are equivalent in their information processing ability (Kolers, 1965). This is evident in the artifically chosen range codings and the presentations of spatial information in most mobility aids (for example the use of "buzz" and "beep" sounds for the coding of the distance to an object in the Russell's Path Sounder).

It is conceivable that, when the spatial information provided by a sensory aid is presented in such a way that the obtained spatial perception closely resembles the sensation of natural spatial perception by the chosen sensory modality, perception of space is more natural, and learning to perceive space through the aid can be easier. Supporting this view, Mills (undated) argued that an object at a distance in space is "out there" in the world and the blind traveller should ideally experience it as an object "out there" but not as an event in his head or upon his skin.

With hearing as the chosen sensory modality, the following section discusses a well known phenomenon in natural auditory perception of space; that is, natural echo location, so as to determine the requirements for incorporating this natural echo location principle in a mobility aid.

2.6.1 <u>Natural echo location and its application in mobility aid</u>

Natural echo location has been known to be used by the blind to detect objects as early as in the 18th Century. The action of the air on the face was thought to be responsible for the perception of obstacles (Diderot, see Supa, Cotzin, and Dallenbach, 1944), hence perception of obstacles by the blind was known as "facial-vision". Furthermore, it was thought that only some gifted blind persons had that ability. However, in a series of studies on facial-vision phenomenon by Dallenbach and his co-workers (Supa, Cotzin, and Dallenbach, 1944; Worchel and Dallenbach, 1947; Cotzin and Dallenbach, 1950; Ammons, Worchel, and Dallenbach, 1953), it was found that auditory stimulation was both a necessary and a sufficient condition for the perception of obstacles. They found that the auditory stimulation was the change in pitch of the sounds (generated by a subject, such as foot steps, jingling of keys, etc.) reflected from the objects.

Bassett and Eastmond (1964) measured this change the pitch (using a flat surface as the object) and found that the pitch, p, of the sound as heard by a subject varied inversely with distance D to the surface:

$p \propto \frac{c}{2D}$ where c = velocity of sound in the air.

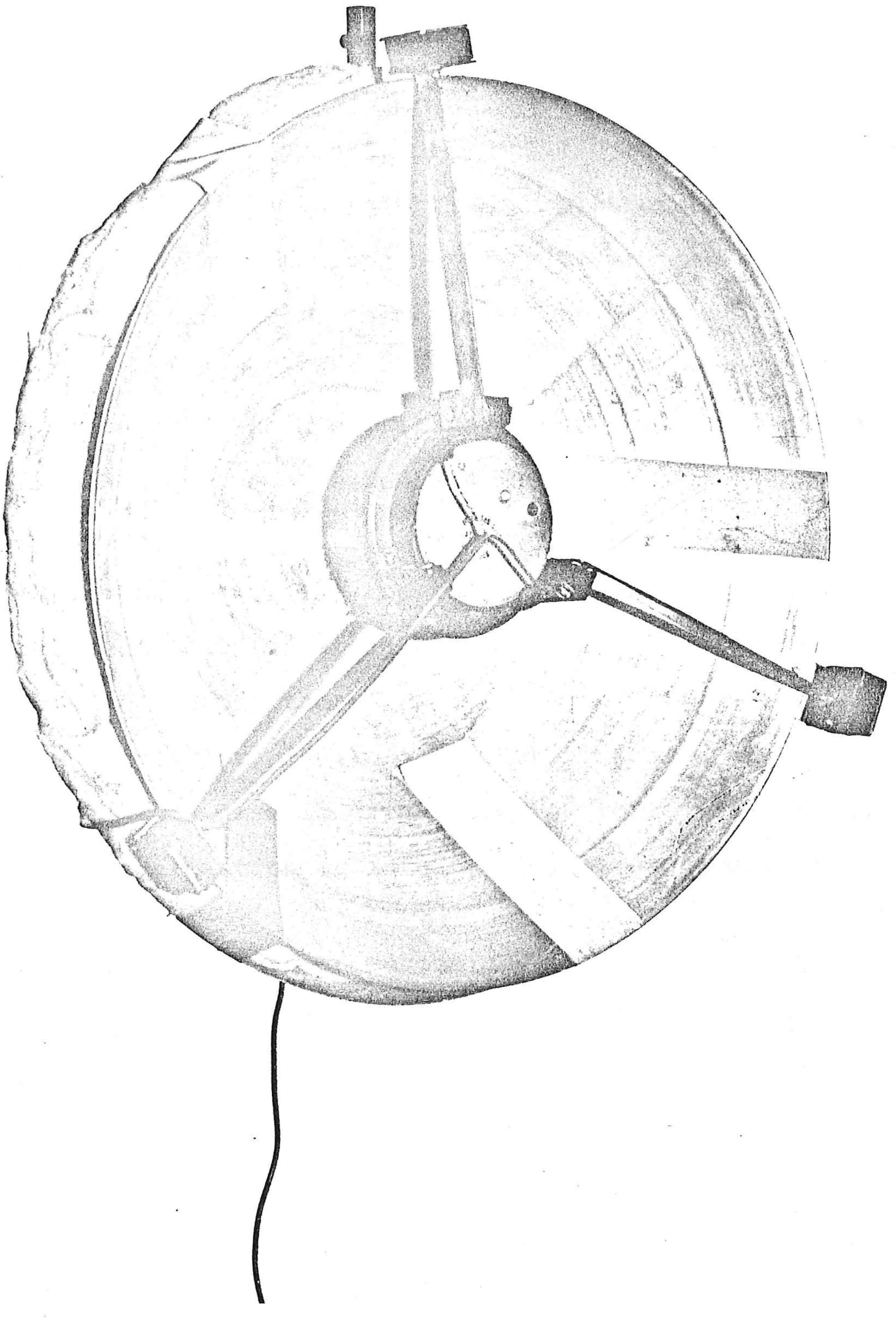
Consequently, it has been argued that any person with normal hearing can be trained to detect obstacles using natural echo location technique (Juurmaa, Suonio, and Moilanen, 1968).

The direction to an object has also been found to be determined rather accurately (mean azimuth errors vary between 4^{o} - 6^{o}) with the subject's self-generated sound (Rice, Feinstein, and Schusterman, 1965; Rice, 1967).

Many attempts have been made to improve the ability of the blind to detect objects, by augmenting the natural echo location sense. Usually, a short click was used to illuminate surrounding objects (Twersky, Witcher, and Washington (see Shrager and Susskind, 1964); Beurle, 1951; Kohler, 1964). The object could then be easily detected by listening for their echoes. The subjects' impressions were that the sounds were heard as if they were emitted from the actual objects. Subjects who used the aids for a long time became capable of detecting objects using their own generated sound (Kay, 1966).

A simplified version of the Beurle's "clicker" was constructed here, using a high quality tweeter (Phillips AD0160) and a 15" parabola disc reflector (fig. 2.4). A lmsec click was used. It was found that poles placed in a large and empty room can be located quite effectively with the clicker. The relative distance between objects could also be noticed. However, judgements of the absolute distance to objects were not accurate.

Although the above clickers have been successful in enhancing the natural echo location, they were not well



A SIMPLE VERSION OF BEURLE'S "CLICKER" TO ENHANCE SPATIAL PERCEPTION BY NATURAL ECHO LOCATION.

FIG. 2.4

accepted as viable mobility aids because of their conspicuousness and the interference of the echoes by ambient sound.

Returning to the problem of a mobility aid with a simple-to-use display it is seen that the conspicuousness and the interference by ambient sound of the clickers can be minimized by using the interrogative signals at the ultrasonic frequencies (ultrasonic transducers can be made very small, say 1 cm in diameter). However, it would be necessary in ultrasonic aids to translate the obtained spatial information down to the audible frequency range and to present the information through earphones. Unfortunately, the use of earphones introduces a new problem: sounds representing objects are heard as "inside the head" instead of "out there" as in natural listening condition (Jeffress and Taylor, 1961). (The determination of object direction in this case is often referred to as lateralization instead of localization as in natural listening condition).

This problem has been recognised by Kay (1966) who argued that to provide a more natural display, his mobility aid (the BSA) must produce the sensation of externalization. Supporting Mills' view, as indicated earlier, Kay also argued that externalization is important because the natural way, in which the spatial information is perceived, can facilitate the perception of spatial patterns (Kay, 1974).

To be able to produce a natural auditory display, it is intended to study the differences between earphones and natural (free field) listening conditions so as to determine the mechanism of localization, in view of possible incorporation of the mechanism into the display of a mobility aid.

The display of a mobility aid can further be simplified by reducing the amount of the provided spatial information. It has been argued that an aid producing sound patterns less complex than those of the BSA may be more easily learned (Kay, Bui, Brabyn, and Strelow, 1977), and may still lead to a good level of overall mobility proficiency. The possible mechanisms to reduce the spatial information provided by a mobility aid are presented in the next section.

2.6.2 Reduction of spatial information collected by a mobility aid

Spatial information collected by a mobility aid can be reduced in three ways:

(i) Pre-processing

One of the experimental pre-processing techniques is to expand the display in the time domain so that the information, while not reduced, can be perceived over a longer period of time. For example, in a pulsed system, a cluster of signals, after expanding, can be perceived as a series of distinct signals, and objects in the cluster can be distinguished. This technique was found to be promising in a laboratory set-up using a tape recorder (Rupf, 1968). However, attemps to utilise the technique in a real-time system, such as the use of a charge coupled device (Slack, 1977), have not been successful as yet.

Another pre-processing technique is to quantise the display. This technique has been used on a pulsed mobility aid by Rudlin (1972) and on the Sonic Torch by Armstrong (1973, p.3). The improvement obtained with the Sonic Torch was negligible while the ease of perceiving space with a quantised pulse system has not yet been well established. Thus, while pre-processing can conceivably reduce the complexity of the auditory stimulus, a suitable algorithm for processing has not yet been perfected.

(ii) Reducing the illuminating field (range, beam width) of the aid

Although conclusive evidences linking the size of the illuminating field of a mobility aid to its effectiveness are lacking, it is conceivable that there is a limit to the field of view of a mobility aid, below which the safety of a user may be endangered. For example, the minimum width of the field being examined should be about 0.5m (shoulder width) at 1m ahead of a user so that the user can safely pass through without the risk of brushing his shoulders against the obstacles.

(iii) Reducing the number of detected objects at any one time

It seems that the number of detected objects at any one time can be reduced to one without affecting the locomotion of a user: In a computer simulation of the BSA, Brabyn (1978) showed that, in a controlled laboratory setting, it was possible to walk around a circle and along or in slalom with a row of poles when only the spatial information about the nearest object was available.

In practice, many mobility aids detect only the nearest object. The Russell Path Sounder and the Mowatt Sensor are typical examples.

The effect of detecting a single object in orientation is, however, not clear, but if the display contains enough information for the recognition of objects, then it is possible that landmarks can be recognised and orientation to these landmarks can be achieved.

It was decided that the proposed aid should detect only one object at a time (the nearest object). Accordingly, the proposed aid is called the Single Object Sensor.

2.7 SUMMARY

For a large proportion of the blind (around 1 million persons), one of the most severe impairments is the lack of mobility. With the introduction of mobility training and the Long Cane, some have become mobile. However, since the Long Cane can only explore the area within a step ahead of a user, travelling is not smooth and the user seems to encounter a considerable amount of psychological stress.

A sensory aid to improve mobility of Long Cane users was widely recognised. Several views have been advanced as to how such a mobility aid should perform. However, since basic knowledge about mobility was not available, these views were often of speculative nature and therefore differ widely. Although it is desirable to build a mobility aid based on concrete evidence, *"the blind are not willing to wait for the result of such basic research, of course, but want to walk around now"*. (Jansson, 1976). As a consequence, a number of mobility aids were built, based on a number of principles and aimed at providing an immediate solution to the problem of blind mobility. One of them is the Binaural Sensory Aid.

Although the aid has been shown to improve mobility of Long Cane users, it has also been argued to be suitable for a very small proportion of the Long Cane users. The main cause is the complexity of its auditory display. It has been argued that a mobility aid with a simpler-to-use display can benefit a larger proportion of the Long Cane users. A simple-to-use display has also been argued to be obtainable by:

1. Reducing the number of detected objects to one;
2. Externalising the sound images so that sounds can be

heard as "outside" instead of "inside" the head.

Such a simple-to-use aid is called the Single Object Sensor. It is envisaged that the Single Object Sensor detects only one object at a time, the nearest to the user. The object would be presented in such a way that the display is heard as if it is actually originated from the detected object; and when no object is detected, no audible sound is produced.

A mechanism to reduce the number of detected objects to one is presented in the next chapter, while the results of a parallel study of externalising a sound image is reported later in the thesis.

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Chapter 3

AUDITORY DISPLAY OF THE SINGLE OBJECT SENSOR

3.1 INTRODUCTION

This chapter mainly concerns with the coding of spatial information in the Single Object Sensor.

In a self-radiating mobility aid, the distance to an object can be accurately obtained by measuring the transit time, i.e., the time a signal takes to propagate from the transmitter to an object and back. A processing technique providing a reliable indication of the transmit time, and at the same time, allowing only the information about the nearest object to be presented to a user, is described in Section 3.2.

Pending the results of a parallel study on externalization of a sound image, the auditory stimulus is considered here to be dichotically presented. Under this headphones listening conditon, the determination of the azimuth angle of a sound source, or lateralization can be determined by Interaural Time Difference (ITD), Interaural Amplitude Difference (IAD) or a combination of both. The choice of a lateralization mechanism for the SOS is dealt with in the remainder of this chapter.

First of all, ways of providing ITD and IAD in a head-mounted mobility aid are described (Section 3.3). The literature on the influences of natural and artificially generated ITD and IAD on auditory lateralization are then briefly reviewed (Section 3.4). Finally, lateralization with a prototype SOS by ITD, IAD and a combination of ITD and IAD is studied (Section 3.5) in an attempt to determine a suitable lateralization mechanism for the SOS.

3.2 CODING OF THE DISTANCE INFORMATION

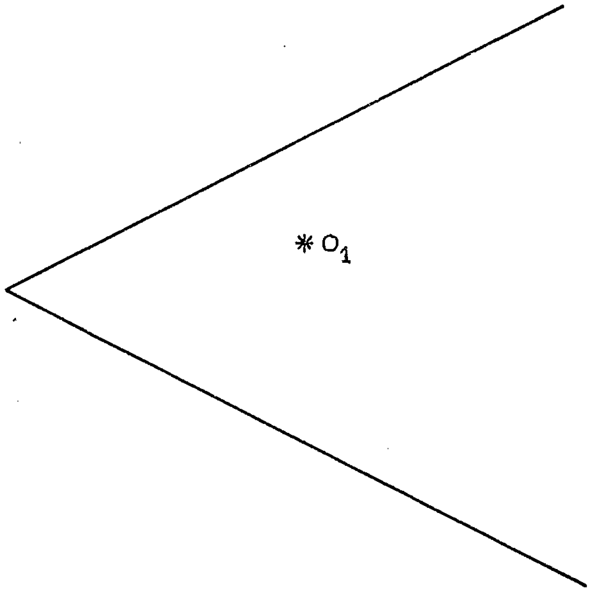
Many techniques can be used to provide a good indication of the transit time, for example the Frequency Modulation technique (as used in the Binaural Sensory Aid), or the Pulsed System (as used in the Russell's Path Sounder). A pulsed system is preferable here, because with a properly chosen pulse width, a pulse system can produce distinct echoes from separated objects in space. Hence echoes from the nearest object can be isolated easily using straightforward electronic techniques.

Consider the illuminating field in the horizontal plane of a hypothetical pulsed mobility aid as shown in Fig. 3.1 a. Assuming that there is an object O_1 at a distance of 2m from the aid. The transmitting pulse and the echo from O_1 are shown in Fig. 3.1 b and 3.1 c respectively. It is seen that information about the size of the object is contained in the envelope of the echoes (the dc pulses, Fig. 3.1 d). Hence if these pulses are presented to a user as the audible stimulus, information about the size and possibly structural information of the object will be conveniently conveyed.

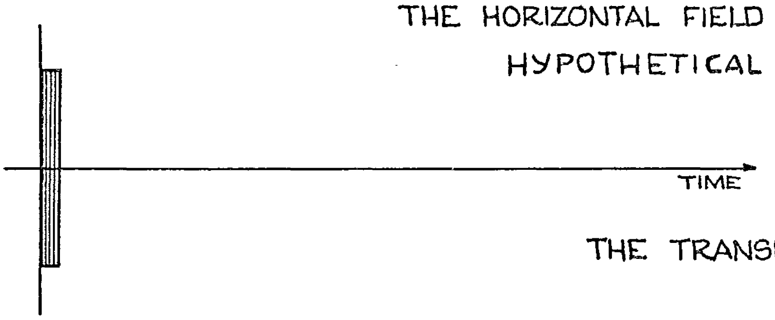
With the echo envelope as the audible stimulus, there are several ways to code the distance information into the auditory display:

(i) Kay (1962) argued that a pulsed system with controlled transmission breakthrough in the auditory display as shown in Fig. 3.1 e can provide a rough indication of the object distance.

However, the permanent presence of the transmission break-through, or the marker pulse, whether or not an object is presented is rather annoying. Furthermore, the precedent

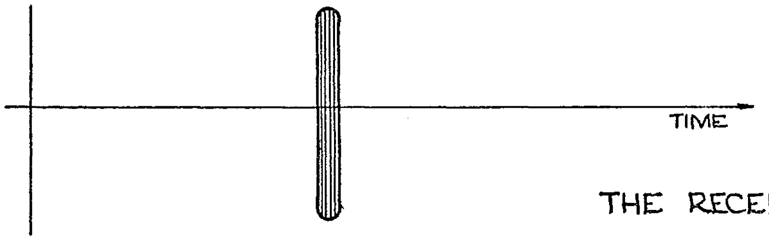


THE HORIZONTAL FIELD OF A HYPOTHETICAL AID FIG. 3.1.a



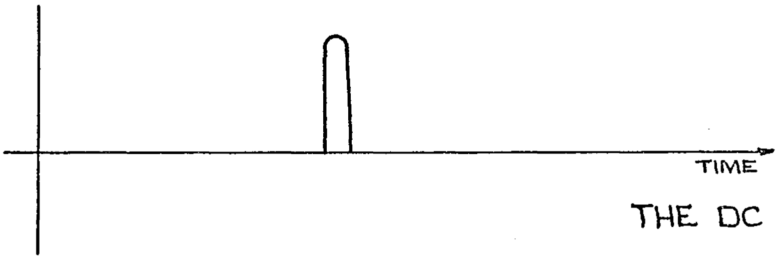
THE TRANSMITTING PULSE

FIG. 3.1.b



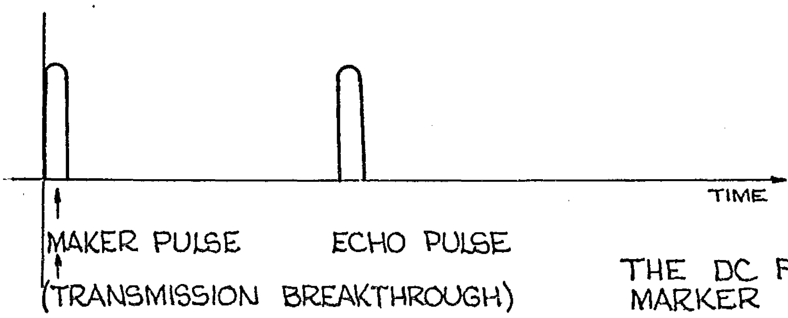
THE RECEIVING ECHO

FIG. 3.1.c



THE DC PULSE

FIG. 3.1.d



THE DC PULSE WITH MARKER PULSE

FIG. 3.1.e

effect (Wallach, Newman and Rosenweig, 1949) due to the marker pulse could inhibit the perception of any echo within several milliseconds from the marker pulse and hence degrading the perception of close-range objects.

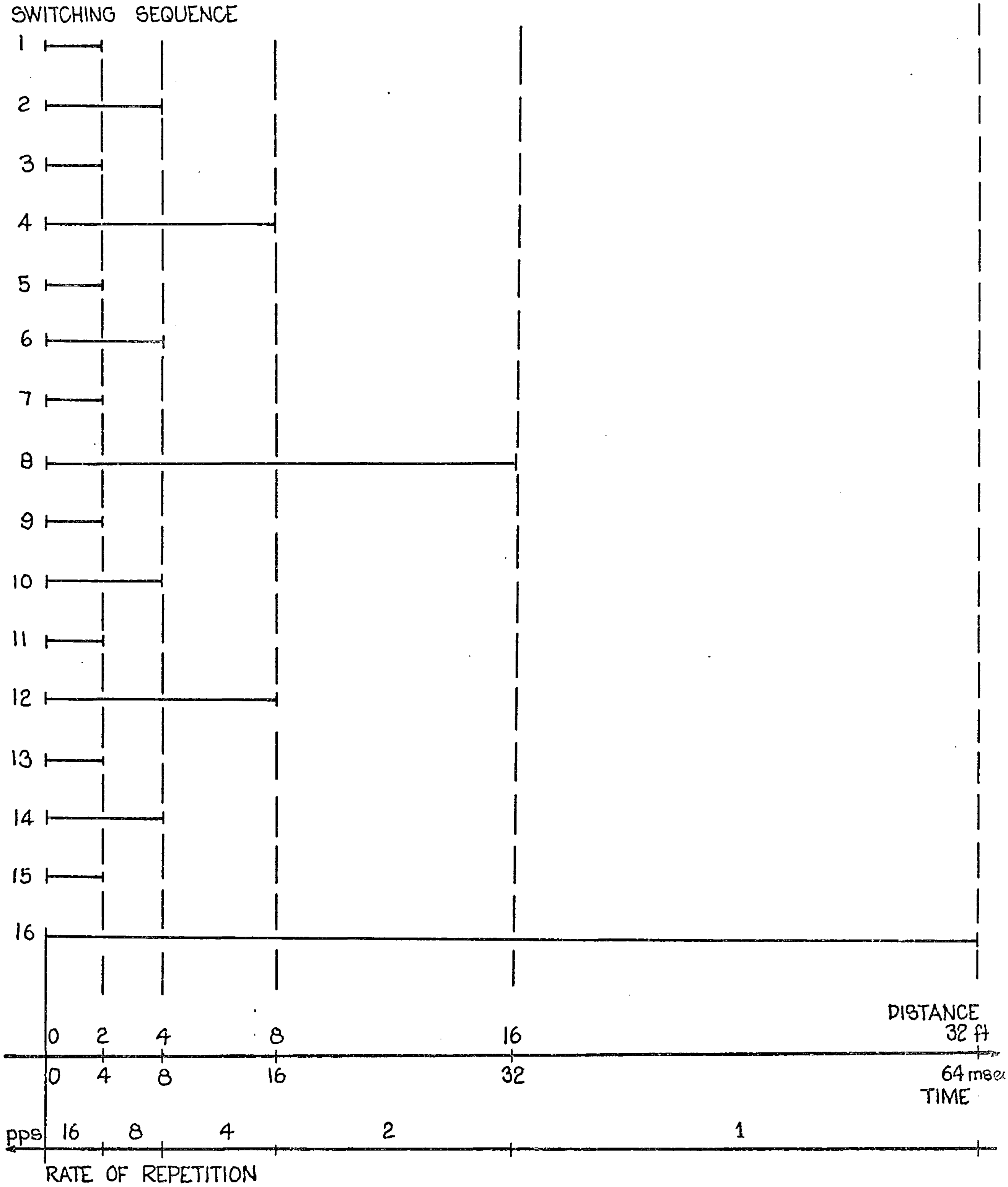
(ii) Rudlin (1972) found that a reliable coding system can be obtained by switching the receiver ON and OFF in a pre-determined sequence so that the pulse rates presented to the user vary in steps, depending on the distance to an object.

A possible switching sequence is shown in Fig. 3.2. In this example, there are five pulse rates corresponding to five sections of the object distance. The echoes from objects within 2 ft distance are presented to a user at the rate of 16 pulses per second (pps) whereas those in the range of 16 ft to 32 ft are presented at the rate of 1 pps. Although this coding has been found to be usable (a user, after sufficient training can identify and separate two clicking rates presented simultaneously), the technique is not suitable here because it does not allow echoes from the nearest object to be isolated easily.

(iii) The coding adopted here was based on a simple but effective coding technique used by Greenspan and Tschiegg (1957) in their Sing-Around Velocimeter. In this system, the transmitter is triggered to transmit again whenever an echo is received. The relation between the rate of repetition FR of the echoes and the distance D to an object is given by:-

$$FR = \frac{c}{2D} \text{ pps}$$

where c = Velocity of sound in the air



SWITCHING SEQUENCE OF AN ULTRASONIC MOBILITY AID RECEIVER (RUDLIN 1972) SOLID LINES INDICATE THE TIME THE RECEIVER IS ON.

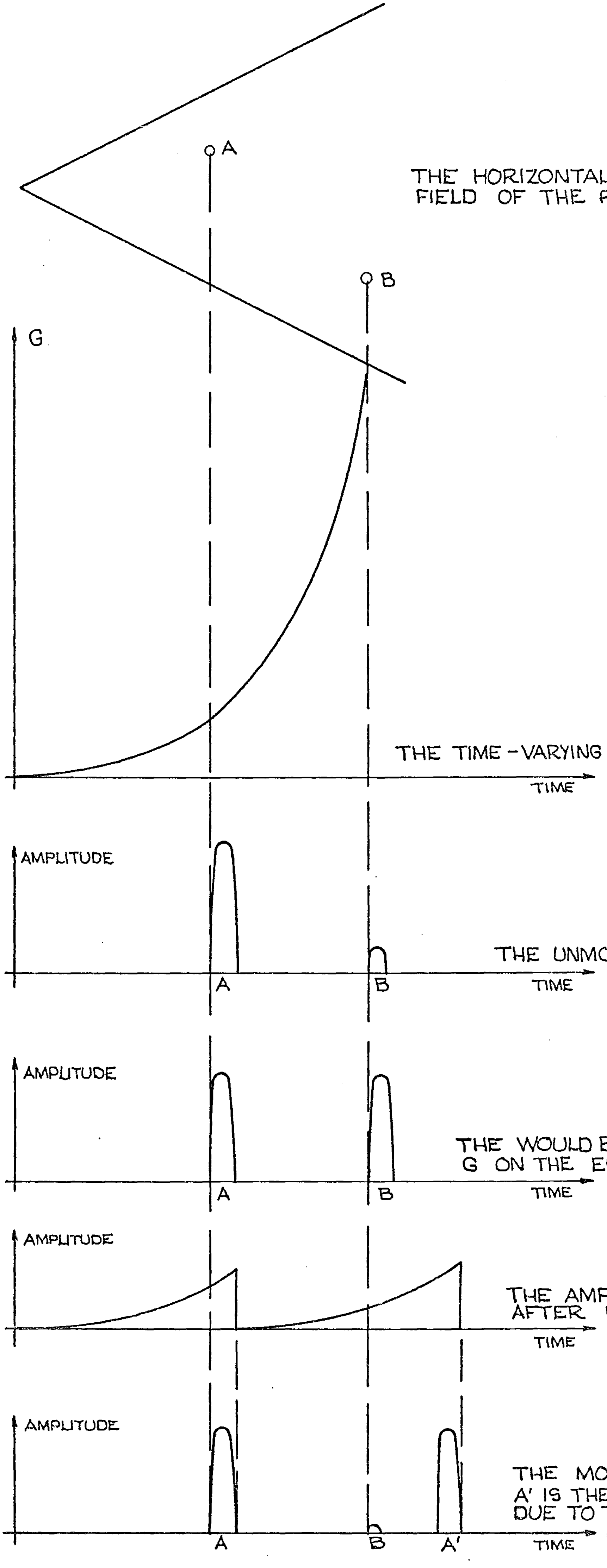
FIG 3.2

This coding has been tried in a mobility aid by Rudlin (1972) and was found to be unworkable because, due to the multiplicity of objects in space, triggering of the transmitter can be unreliable. However, reliable triggering can be restored by using a time-varying-gain amplifier to modify the amplitudes of echoes so that only echoes from the nearest object are strong enough to trigger the transmitter. A diagram showing the mechanism of triggering the transmitter is shown in Fig. 3.3. The mechanism is briefly described below:-

Suppose that there are two objects of the same size, A and B, in the viewing field of the device (Fig 3.3 a), the unmodified echoes would have the forms as shown in Fig. 3.3 c. The echo from object B is smaller due to the spreading and absorption loss of ultrasonic signals in the air. If a time-varying-gain amplifier with the gain $G = t^4 + bt^2$ (Fig. 3.3.b) is used to compensate for these losses, then the echo amplitudes would be modified such that identical objects at different distances would have the same amplitude level (Fig. 3.3 d).

However, since only echoes from the nearest object are required, every time an echo is received the time-varying-gain amplifier is reset (Fig. 3.3 e) and another pulse is transmitted. Thus echo from object B, already lower in amplitude due to its farther distance, is amplified with a much lower gain. Consequently, it will not be strong enough (Fig. 3.3 f) to trigger the transmitter and will not be passed through to the audio stage.

This pre-processing technique was incorporated in an experimental model of the SOS and was found to function satisfactorily. False triggering due to multiplicity of objects in the environment as reported by Rudlin (1972) was



THE HORIZONTAL VIEWING FIELD OF THE PROPOSED SOS
FIG. 3.3. a

THE TIME-VARYING-GAIN AMPLIFIER
FIG. 3.3. b

THE UNMODIFIED ECHOES
FIG. 3.3. c

THE WOULD BE EFFECT OF G ON THE ECHOES
FIG. 3.3. d

THE AMPLIFIER GAIN AFTER RESETTING.
FIG. 3.3. e

THE MODIFIED ECHOES. A' IS THE ECHO FROM A DUE TO THE 2nd TRANSMITTING PULSE
FIG. 3.3. f

considerably reduced. For two objects of similar size and in the same direction, there is no possibility of wrong triggering, regardless of their relative distance. When a closer object is smaller or in different direction than the farther object, the transmitter may briefly try to trigger on both objects. The range where false triggering may occur is shown in Fig. 3.4 for two objects of sonar cross-section A and 2A. The effect of multiple triggering on the spatial perception will be dealt with later in the thesis.

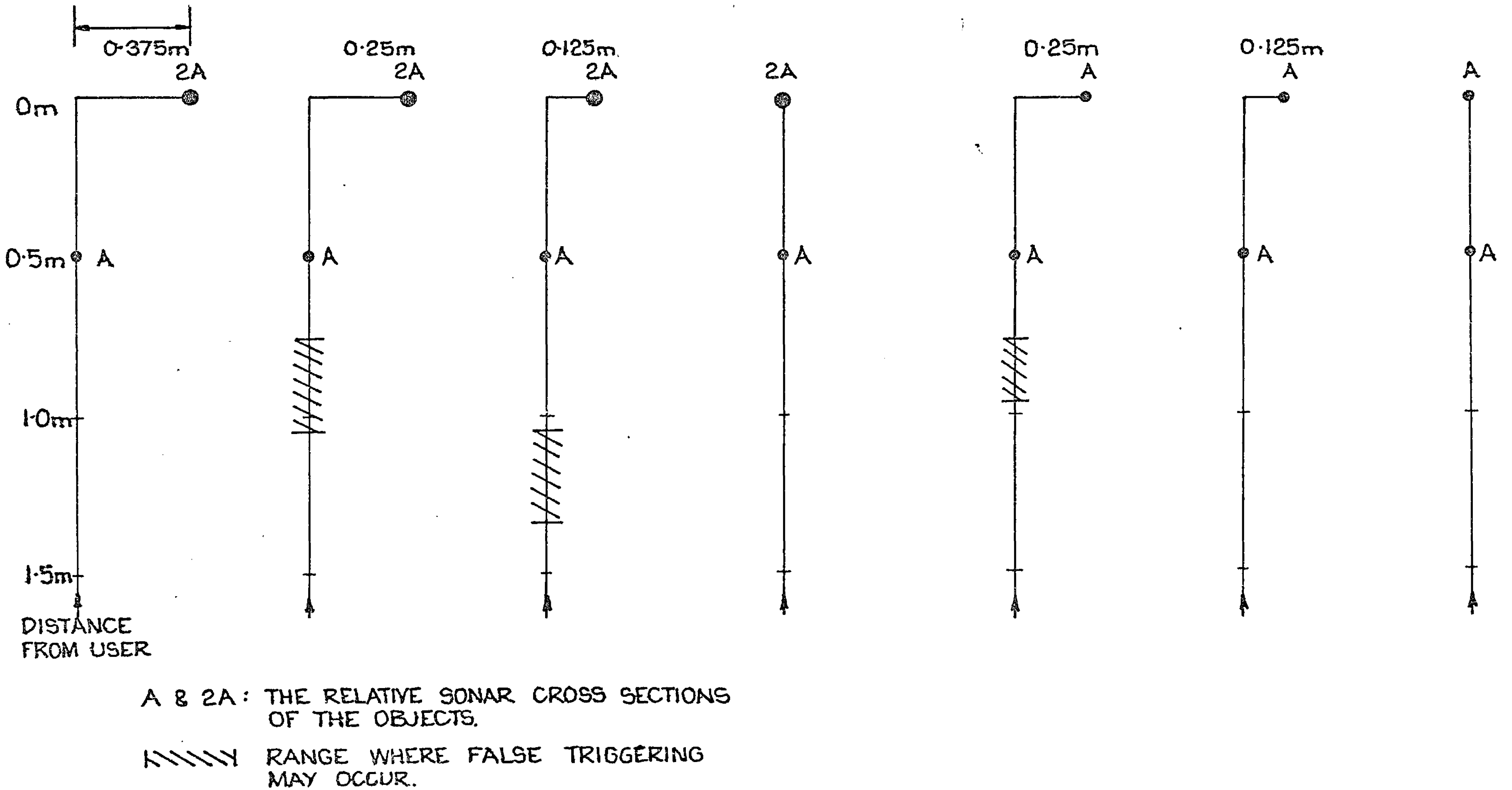
It is interesting to note that in the Sing-Around triggering scheme, the rate of repetition of the echoes varies in the same manner as the pitch of sounds reflected from a flat surface observed in the natural echo location phenomenon (Bassett and Eastmond, 1964).

3.3 WAYS OF PROVIDING ITD AND IAD

In the SOS, ITD, IAD or a combination of the two can be realised by suitable arrangements of the receiving transducers.

(i) ITD is provided by mounting the two receiving transducers a distance L apart (Fig. 3.5 a), ITD is then determined by:-

$$\mathrm{ITD} = \frac{1}{c}\sqrt{\left(D^2 + \left(\frac{L}{2}\right)^2 + DL\sin\theta\right)^2 - \left(D^2 + \left(\frac{L}{2}\right)^2 - DL\sin\theta\right)^2} \qquad 3.1$$



THE EFFECT OF RELATIVE SIZE AND DISTANCE OF OBJECTS IN FALSE TRIGGERING OF THE TRANSMITTER.

FIG. 3.4.

Where D = Object distance

L = Transducer separation

c = Velocity of sound in the air

Θ = Azimuth angle of the object.

In the limit where $D \gg L$,

$$ITD = \frac{L}{c} \sin \Theta \qquad 3.2$$

L is taken to be 16 cm to provide a good agreement with the actual propagation path length differences (Rowell, 1970). The ITD is shown in Fig. 3.5 b.

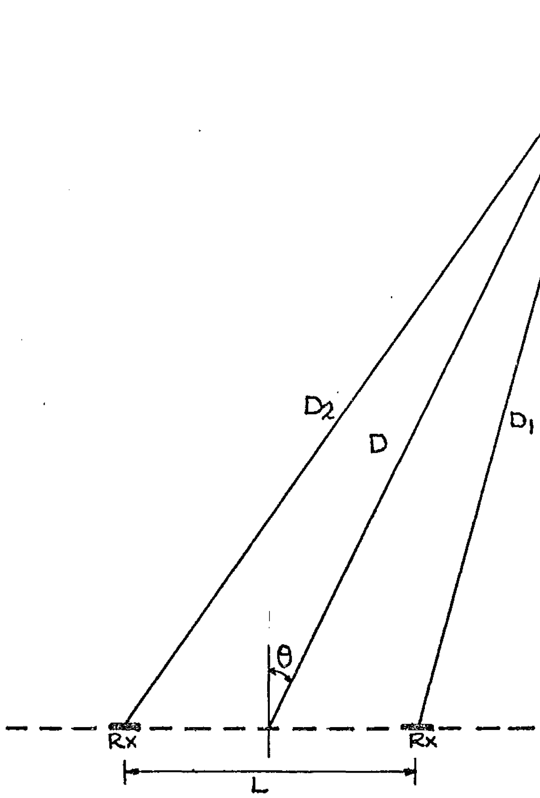
(ii) IAD can be provided by using a pair of receiving transducers with suitable polar response $D(\Theta)$, placed at a certain splay angle α, so that the differences in the echo intensities (due to the polar responses of the two receivers) match the normal IAD. The required polar response has been extensively studied by Rowell in 1970. He argued that an azimuth estimator $\bar{\Theta}$ of the subject's response in a lateralization experiment can be written as follows:

$$\bar{\Theta} = K\log_e \left(\frac{A1}{A2}\right) + \Theta_o \qquad 3.3$$

where A_i = sound amplitude in the i^{th} channel

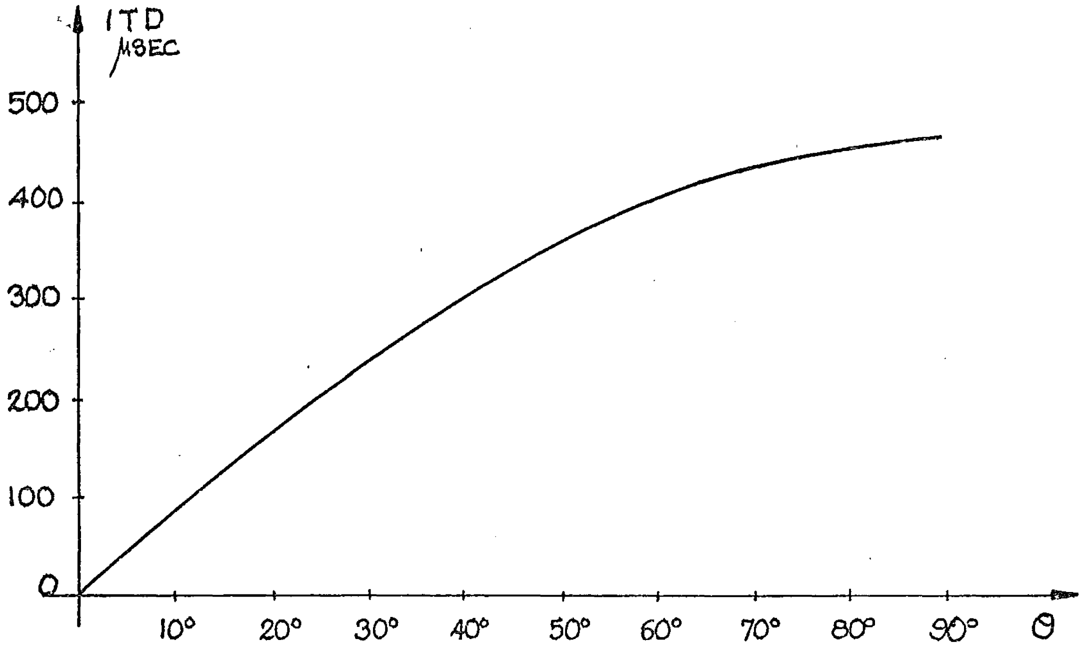
K = a lateralization constant

Θ_o = initial offset in the subject's judgement of the median plane



RECEIVERS ARRANGEMENT TO PROVIDE ITD

FIG. 3.5. a



ITD vs AZIMUTH ANGLE θ

FIG. 3.5. b

With the amplitude of the echoes in the i^{th} channel in the form:-

$$A_i(\Theta) = C_i(\Theta) \cdot G(\Theta) \cdot D(\Theta + (-1)^i \alpha) \qquad 3.4$$

where $C_i(\Theta)$ = amplitude gain in the i^{th} channel

$G(\Theta)$ = polar response of the transmitting transducer.

$D(\Theta)$ = polar response of the receiving transducer

α = displacement angle of the response $D(\Theta)$ from the median plane, i.e., the splay angle

then the estimator $\bar{\Theta}$ is given by:

$$\bar{\Theta} = K\log_e \frac{C_1 D(\Theta-\alpha)}{C_2 D(\Theta+\alpha)} + \Theta_o \qquad 3.5$$

For the estimator $\bar{\Theta}$ to be the same as the true azimuth angle, Θ, from e.g., 3.5, the polar response $D(\Theta)$ of the receiving transducer is required to have the form:-

$$D(\Theta+\alpha) = \frac{C_1}{C_2} \exp\left(\frac{\Theta o}{K}\right) \cdot D(\Theta-\alpha) \exp\left(-\frac{\Theta}{K}\right) \qquad 3.6$$

Thus when $\dfrac{C_1}{C_2} = \exp\left(-\dfrac{\Theta o}{K}\right)$ 3.7

We have $D(\Theta) = \exp\left(-\dfrac{\Theta^2}{4\alpha K}\right)$ 3.8

Equations 3.7 and 3.8 indicate that:-

If the gains of the two receiving channels are properly adjusted according to equation 3.7 to offset the initial error Θ_o and if the receiving transducers with the polar response of the gaussian form $D(\Theta) = \exp\left(-\frac{\Theta^2}{4\alpha K}\right)$ are used, then:

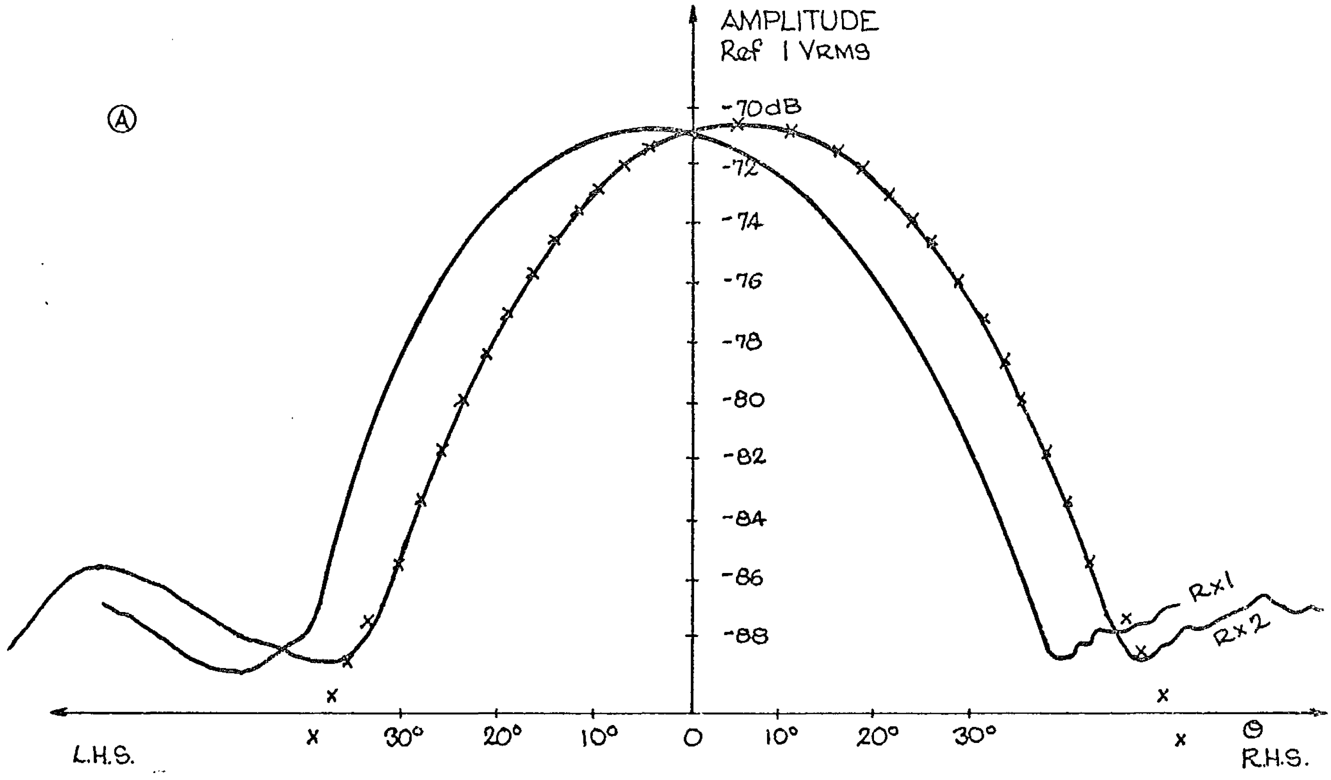
$$\alpha = \frac{\Psi_{\frac{1}{2}}^2}{96\beta}$$

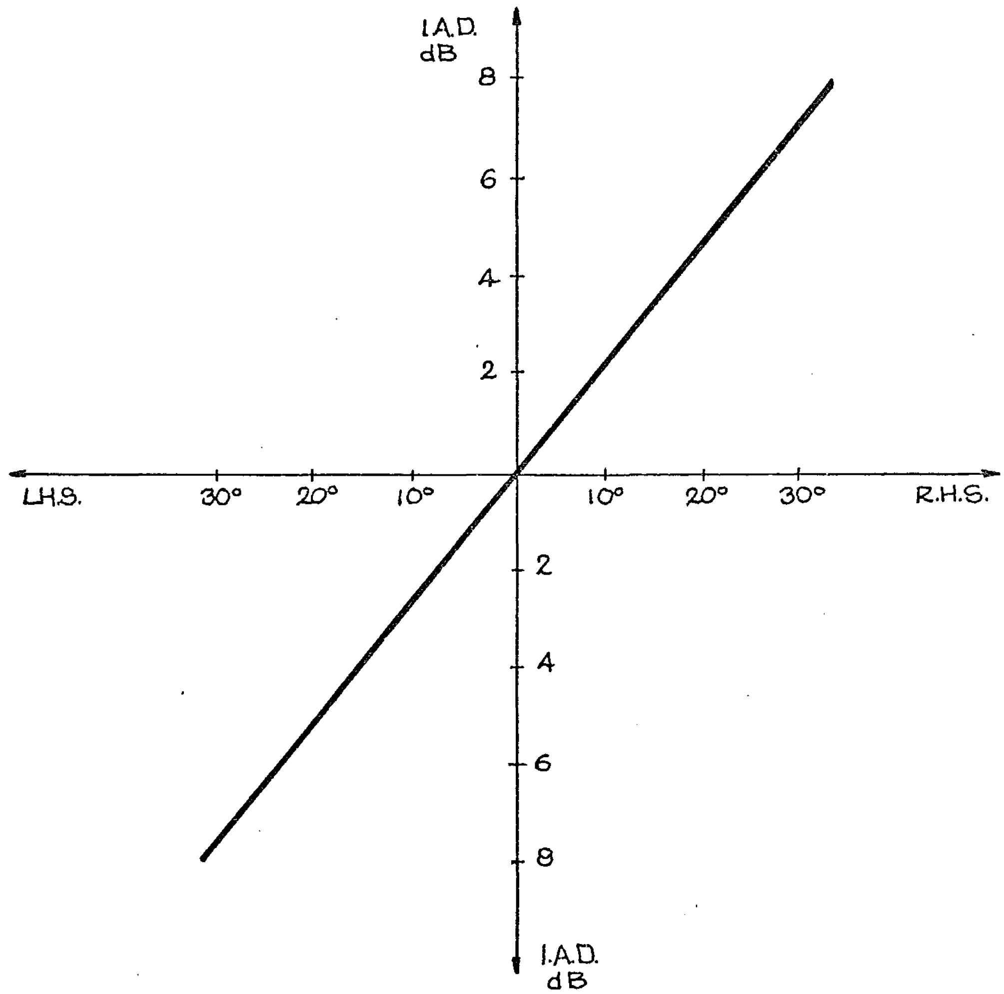
where $\psi_{\frac{1}{2}}$ = half power beam width of the receiving transducer

$$\beta = \frac{K}{8.686}$$ = lateralization constant in degrees/dB

In other words, a value of the splay angle α, can be chosen to match any lateralization constant β of the human auditory system.

Fig. 3.6 a shows the theoretical polar response of an idealized transducer $D(\Theta) = \exp\left(-\frac{\Theta^2}{4\alpha K}\right)$ (dots) and the actual responses of 48^o beam width transducers at $\pm 6^o$ splay angle (solid lines). The IAD produced are shown in Fig. 3.6 b for $-30^o < \Theta < 30^o$. For small Θ, the variation of the actual polar response from the idealized curve produces an insignificant error. For $|\Theta| > \psi_{\frac{1}{2}}$ the side lobes and zeroes in the actual transducer polar response produce a large variation in the IAD and can make the IAD cue erroneous and unreliable. However, if a directional transmitter is used to illuminate the field where only the receivers' main beams are operating, the effects of the





Ⓐ ——— THE POLAR RESPONSES OF A 6° SPLAY ANGLE RECEIVERS SYSTEM

X THE POLAR RESPONSE OF AN IDEALIZED TRANSDUCER $D(\theta) = \exp\left(-\frac{\theta^2}{4\alpha K}\right)$ OF THE SAME BEAM WIDTH.

Ⓑ THE CORRESPONDING I.A.D. FOR $-30° < \theta < 30°$

FIG. 3.6

side lobes in the receiving transducer's polar response can be considerably reduced.

3.4 EFFECTS OF ITD AND IAD ON AUDITORY LATERALIZATION: A LITERATURE REVIEW

Under natural listening conditions, ITD is produced by the difference in path lengths that a sound takes to reach the two ears of a listener. It varies from 0 μsec for sound at the median plane to approximately 500 μsec for sound at 90° to the median plan. The difference in path length also produces an interaural phase difference, IPD, which is related to ITD by: IPD = ITD x $2\pi f$. IPD, therefore, varies from 0 for sound at the median place to $n2\pi$ at 90° where n is a function of the frequency of the sound.

The IAD, on the other hand, is influenced not only by the difference in attenuations of the sounds due to the difference in path lengths, but also by the shadow of the head and the ears. IAD has been shown to vary with azimuth angles as well as with the sound's frequency.

Due to the difference in the producing mechanisms of ITD and IAD, it is not surprising to find that ITD and IAD influence localization of sounds at different frequency ranges.

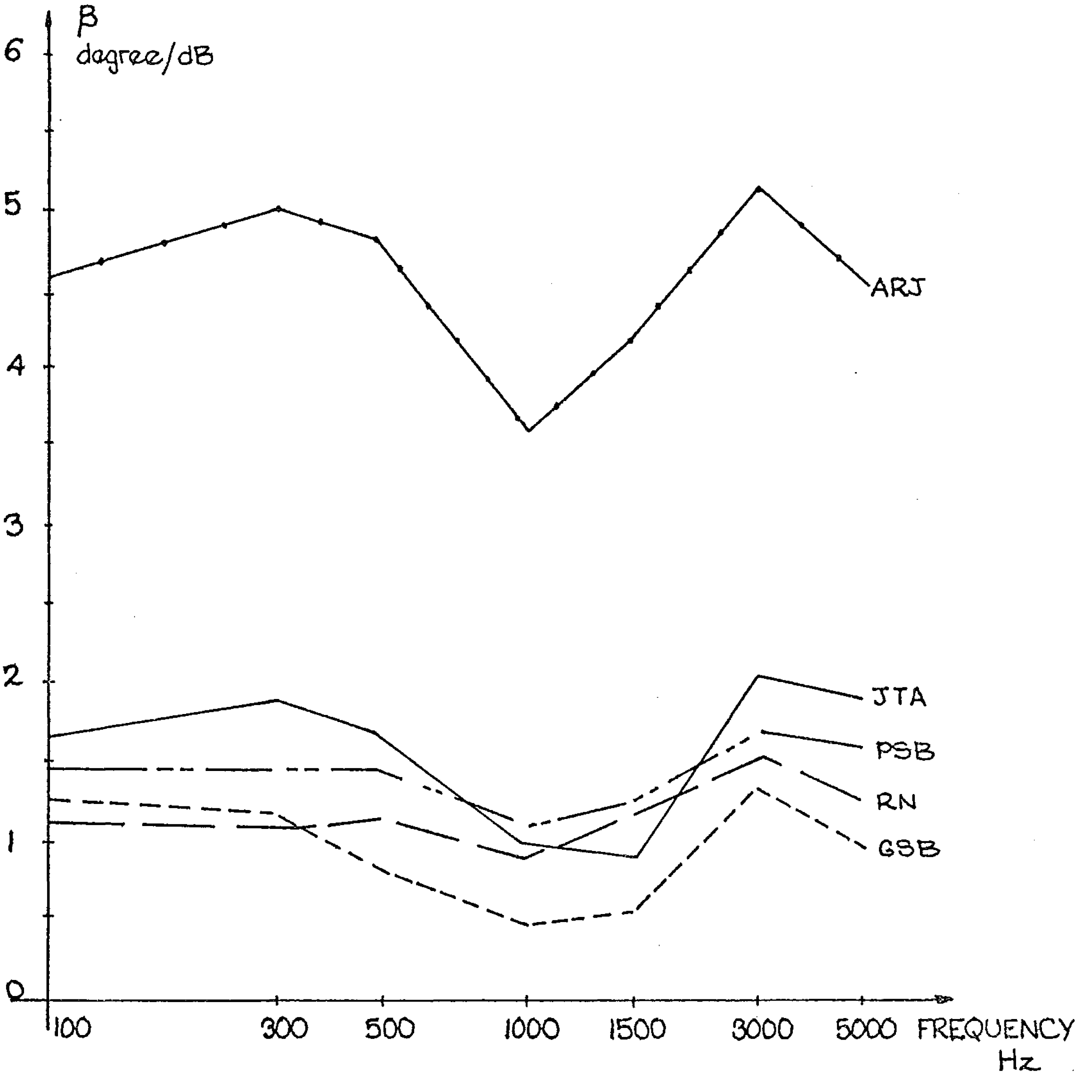
In general, ITD has been shown to influence localization of tones below 1500 Hz, while localization of tones above 1500 kHz is mainly determined by IAD (Sandel, Teas, Fedderson and Jeffress, 1955, Zwislocki and Feldman, 1956; Mills, 1960). The shift of localization mechanism from ITD to IAD can be attributed to the ambiguity in IPD at high frequencies and to the relative ineffectiveness of the head as a sound shadow at low frequencies.

The ambiguity in IPD at high frequencies deserves a more detailed discussion:

For frequencies above 1500 Hz, the sound wavelength is less than 0.228 m while the minimum acoustical path between the two ears is averaged to about 0.230 m. Thus the acoustic paths exceed one full wave length. Ambiguity arises because the human nervous system is unable to distinguish IPD of $2\pi+\theta$ from IPD of θ. Substantiating this view, Mills (1972) argued that since the population of the auditory nerve cells can only fire in synchrony with signal below 1000 Hz and since the synchronized firing rate of the nerve is necessary for unambiguous phase information, the ambiguity in localization by ITD is expected to increase for sounds with frequencies above 1000 Hz.

The above discussion applies only to free field listening condition where the effect of the shadow of the head on IAD is negligible at low frequencies. With artificially generated and dichotically presented sounds, where ITD and IAD can be set at any arbitrary value, the effects of ITD and IAD on auditory lateralization can be different:

Rowell (1970) studied the lateralization of pure tones by artificially generated IAD and found that it can be used to lateralize tones up to 5 kHz. The lateralization constant β (azimuth angle/ IAD in degrees/dB) was found to be a function of frequency and to vary with individual subjects (Fig. 3.7). IAD can also be used to lateralize complex sounds (sounds with frequency spectrum extended over a wide range of frequencies), such as clicks or periodic pulses. Intensity differences up to 22 dB were reported for completely lateralized sounds.



THE VARIATION OF THE LATERALIZATION CONSTANT β WITH FREQUENCIES AND ACROSS SUBJECTS. (ROWELL 1970)

FIG. 3.7

ITD, however, can only be used to lateralize sounds of low frequencies ($f < 1500$ Hz), or complex sound with low rates of repetition ($FR < 1500$ pps). At high frequencies or high FR, the IPD confusion with θ and $2\pi + \theta$ again happens. Artificially generated ITD can be varied over a wide range, the use of ITD up to 15 msec has been reported (Guttman, 1962).

Lateralization under various combinations of ITD and IAD has also been experimented. Most of the experiments were concerned with the trading of ITD by IAD and vice versa. In general, it was found that ITD and IAD can be traded off, although the trading is not complete and occasions of double images have been reported. (Moushegian and Jeffress, 1959; Hafter and Jeffress, 1968; Hafter and Carrier, 1972; Gilliom and Sorkin, 1972).

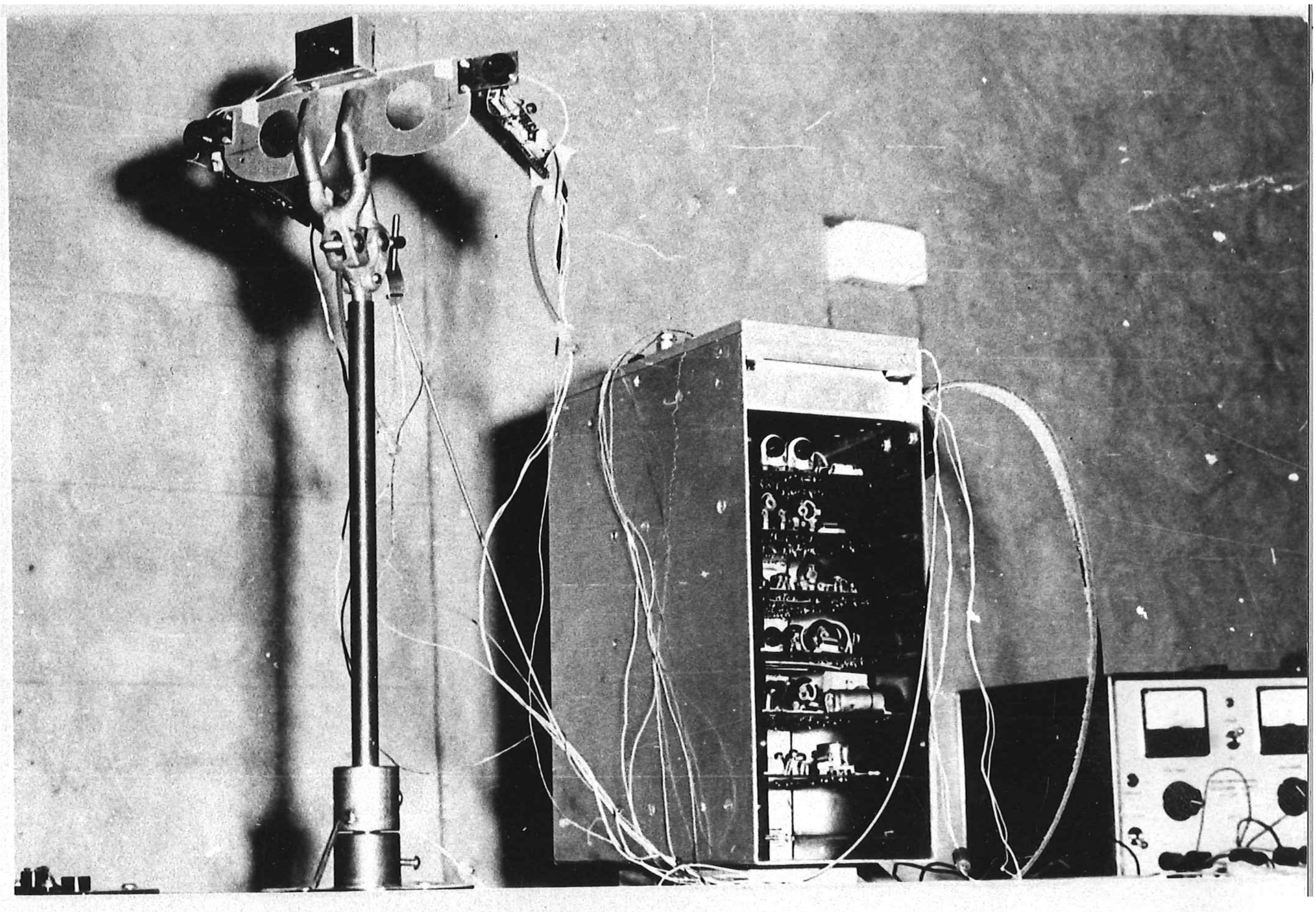
3.5 AUDITORY LATERALIZATION WITH AN EXPERIMENTAL MODEL OF THE SINGLE OBJECT SENSOR

3.5.1 Introduction

(i) Description of an Experimental Model

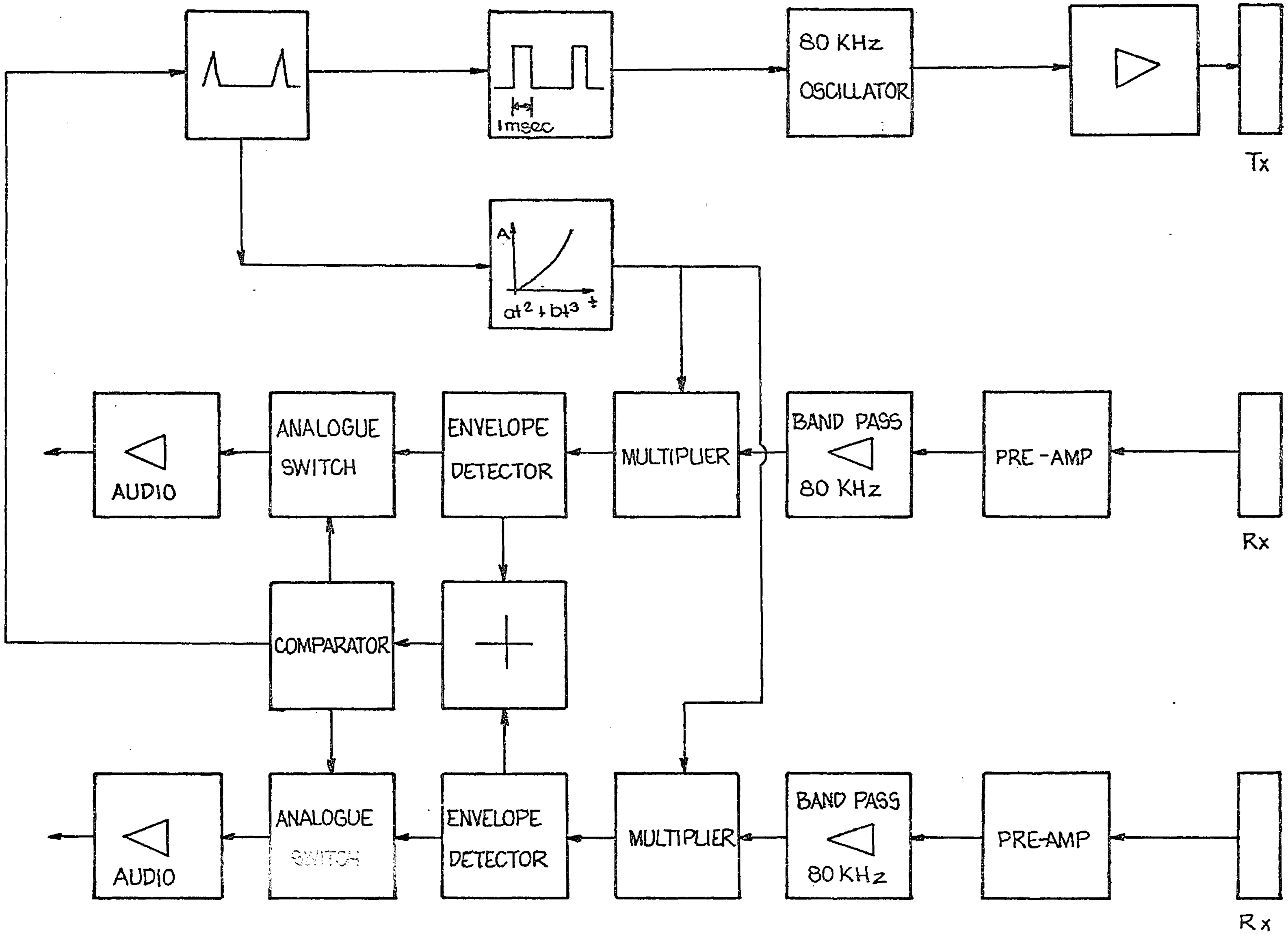
Basically, the experimental model (Fig. 3.8) consists of a spectacle frame and a control box. The transmitting, receiving transducers and the associated pre-amplifiers are mounted on the spectacle frame. (The positions of the receiving transducers to provide IAD and ITD will be discussed later). The remainder of the circuitry is housed in the control box. The block diagram of the aid is shown in Fig. 3.9. The basic operation of the aid is as follows:

Initially a burst of 80 kHz signal (1 msec duration) is transmitted. Echoes from surrounding objects, after amplification



AN EXPERIMENTAL MODEL OF THE SOS

FIG 3.8



BLOCK DIAGRAMS OF AN EXPERIMENTAL MODEL OF THE SINGLE OBJECT SENSOR

FIG. 3.9

are multiplied with a time varying signal (as mentioned in Section 3.2), and then rectified. The envelopes of the echoes are then compared with a preset threshold level. If their amplitudes are above the threshold level they will be passed through to the audio stage and presented to a user. At the same time, the transmitter is retriggered to transmit another burst of 80 kHz signal. Otherwise another burst is transmitted 16 msec after the intial burst, and so on. The circuit diagrams of the experimental model are shown in Appendix 1.

(ii) The Auditory Stimulus

The auditory stiumuls of the SOS from a wooden pole at 1.5 m range is shown in Fig. 3.10. It can be approximated by a train of periodic pulses filtered by a low pass filter. With this stiumulus, it is possible to use either ITD or IAD as the lateralization mechanism.

ITD: The rate of repetition FR of the echoes is given by

$$FR = \frac{C}{2D}$$

It rarely exceeds 1500 pps (which corresponds to an object distance of 0.1 m), hence the phase ambiguity normally associated with lateralization at high rates of repetition ($FR > 1500$ pps) may not present.

IAD: The Fourrier transform, F, of periodic pulses is given by:-

$$F = 2n.A.\zeta.FR \sum_{n=-\infty}^{n=+\infty} Sa(n\pi.\zeta.FR)\ \delta\ (\omega - n\omega_o)$$

where ζ = the pulse width

FR = rate of repetition of periodic pulse $= \frac{\omega_o}{2\pi}$

The energy contained in the signal spectrum is concentrated in the region below the 1st zero of the $\frac{\sin x}{x}$ function. Therefore most of the energy of the Single Object Sensor's sound is concentrated below $f = \frac{1}{\zeta}$.

$$\text{with} \quad \zeta = 1 \text{ msec}$$
$$f = 1000 \text{ Hz}$$

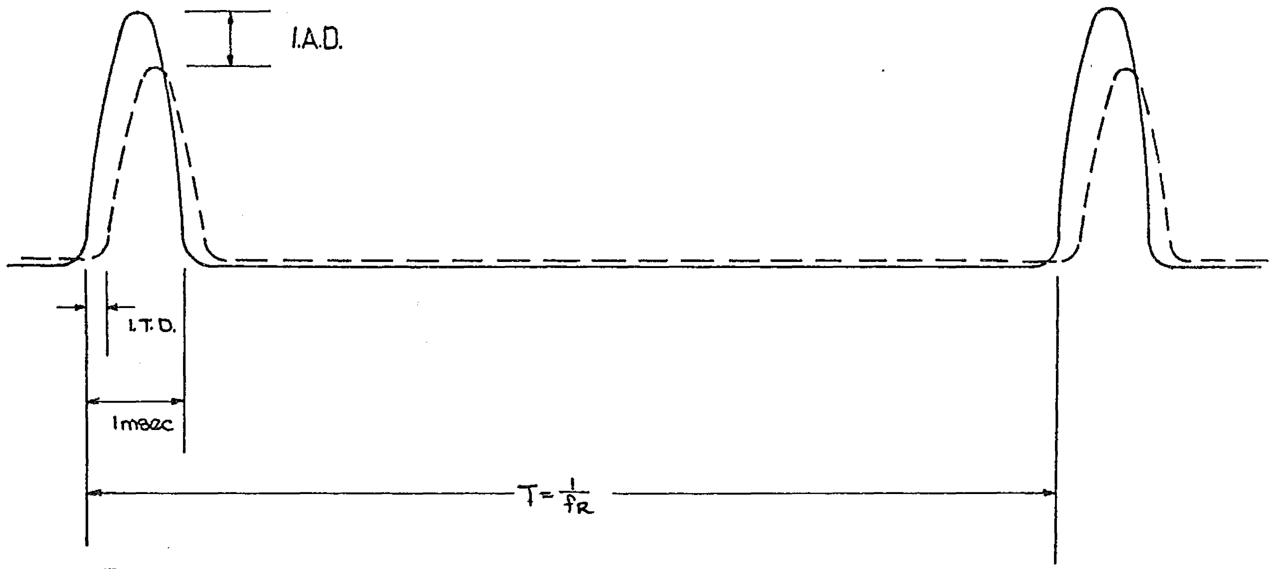
Since the auditory display of the Single Object Sensor operates in the more linear region of the lateralization constant β ($f < 1000$ Hz, Fig. 3.7), it is expected that the lateralization acuity will not be seriously impaired by the variation of β with frequency.

In the following series of experiment, lateralization by ITD, IAD and a combination of ITD and IAD with the experimental model are assessed to determine the most suitable lateralization mechanism for the Single Object Sensor.

3.5.2 General Procedure and Apparatus

The IAD, ITD and a combination of IAD and ITD could be generated with the arrangement of the receiving transducers as shown in Fig. 3.11 a, b, c respectively. Care has been taken to insure that no IAD was presented in the ITD only experiment.

The experiments were conducted in a sound treated room (17 m x 11 m). A wooden pole , 2.5 cm in diameter and placed at 1.5 m from the aid,was used as the object. The object distance was chosen to be half of the original proposed range of the aid. The auditory stimulus representing the object (train of 1 msec clicks, 112 pulses per second) was presented to the subject through a pair of KOSS PRO A4 headphones. Input to the headphones was disconnected between presentations to obviate any unwanted cues.

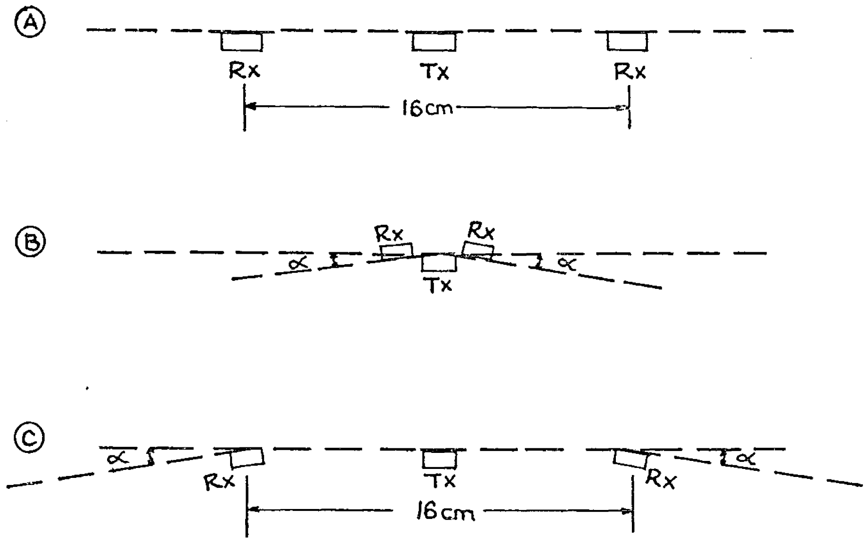


——— AUDIO OUTPUT IN THE RIGHT CHANNEL.

– – – AUDIO OUTPUT IN THE LEFT CHANNEL.

THE AUDITORY DISPLAY FOR AN OBJECT AT 1·5 METRE RANGE AND AT SOME ANGLE TO THE R.H.S.

FIG. 3.10



Tx = TRANSMITTER
Rx = RECEIVER
∝ = SPLAY ANGLE

TRANSDUCERS ARRANGEMENT TO PRODUCE

Ⓐ I.T.D. ONLY

Ⓑ I.A.D ONLY

Ⓒ I.T.D. x I.A.D.

FIG. 3.11

The subject was seated in a corner of the room, facing the corner, with no visual information about the direction of the object. He was asked to produce a tactile sensation on his forehead (using a tactile senation generator similar to that used by Von Bekesey (1960, Fig. 3.12) and align the tactile image with the image produced by the auditory stimulus. The subject can change the direction of the tactile sensation but has no control over the direction of the auditory image. The latter, which was controlled by the experimenter, was changed by rotating the mounting shaft of the spectacle frame.

A protractor, mounted at the base of the mounting shaft, provided a mean to measure the angle of rotation, while a potentiometer, connected to an arm of the tactile sensation generator, allowed the direction of the tactile image to be read off a moving coil meter.

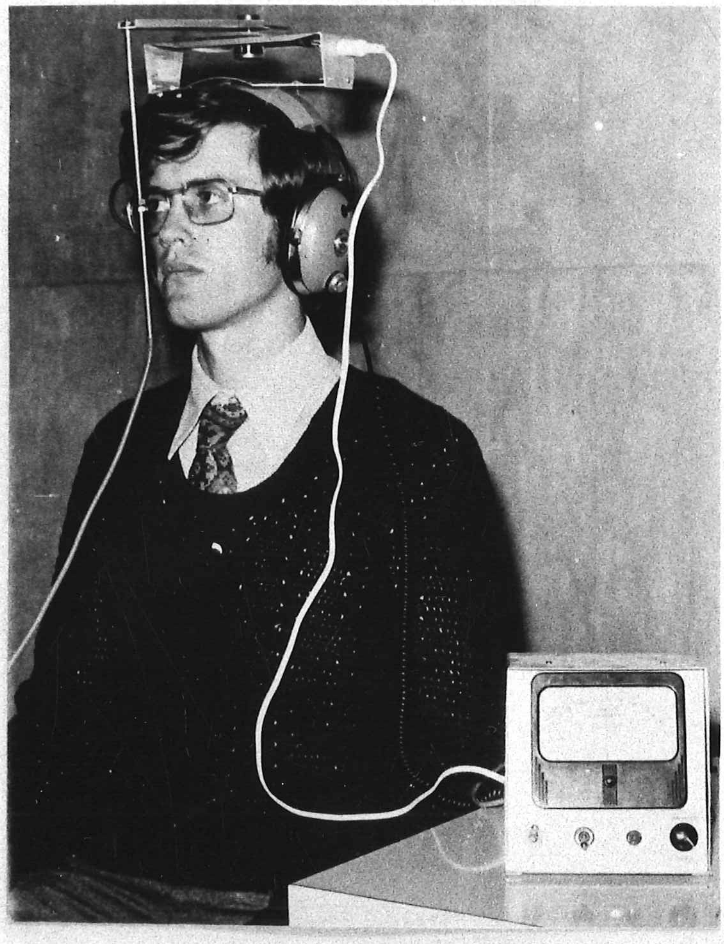
Five subjects participated in the experiments, none had participated in any psychoacoustical experiment before. Audiometric tests showed no hearing anomalies.

3.5.3 Experiment 1: Lateralization by IAD

Procedure

In this experiment, the auditory image of the wooden pole was produced by using IAD only. The splay angle α (Fig. 3.11 b) was chosen to produce a lateralization constant of β = 2.5 degree/dB, which was within the range of the lateralization constant used in the Binaural Sensory Aid. Seven auditory images were used, corresponding to the 7 azimuth angles θ of:-

$\theta = 0^{o}$ (median plane), 10^{o}, 20^{o} and 30^{o} to the left and the right of the median plane. The auditory images were



TACTILE SENSATION GENERATOR

FIG 3.12

presented to the subjects randomly five times for each azimuth angle.

Results

Subjects were able to align the auditory image to the tactile image, although some difficulties were reported at the beginning of the experiment. The reported angles are plotted in Fig. 3.13 a, against the true angles. The within subject standard deviations of the reported angles are shown in Fig. 3.13 b.

There was a shift in the reported angle toward the RHS. The shift, Θ_o in equation 3.5, was probably due to an unbalance in the response of subject's ears and in the amplification of the two receiving channels.

3.5.4 Experiment 2: Lateralization by ITD

In this experiment, ITD due to the difference in the path lengths of echoes was used as the sole lateralization constant. The receiving transducers were mounted 16 cm apart as shown in Fig. 3.11 a.

The apparatus, procedure and subjects were the same as in the IAD lateralization experiment, however, only five object azimuth angles were used:-

$\Theta = 0^o$ 10^o and 20^o to the right and the left hand side of the median plane of the aid.

Results

There were appreciably more difficulties to align the auditory image to the tactile sensation with ITD than with IAD, especially at the median plane position.

The subjects reported angles are plotted in Fig. 3.14 a. It showed an enormous variation in the reported angles, especially at the median plane. The standard deviations are shown in Fig. 3.14 b.

3.5.5 Experiment 3: Lateralization by ITD and IAD

The receiving transducers were arranged as shown in Fig. 3.11 c, with splay angle α and 16 cm apart. The apparatus, procedure and subjects were the same as in the IAD experiment.

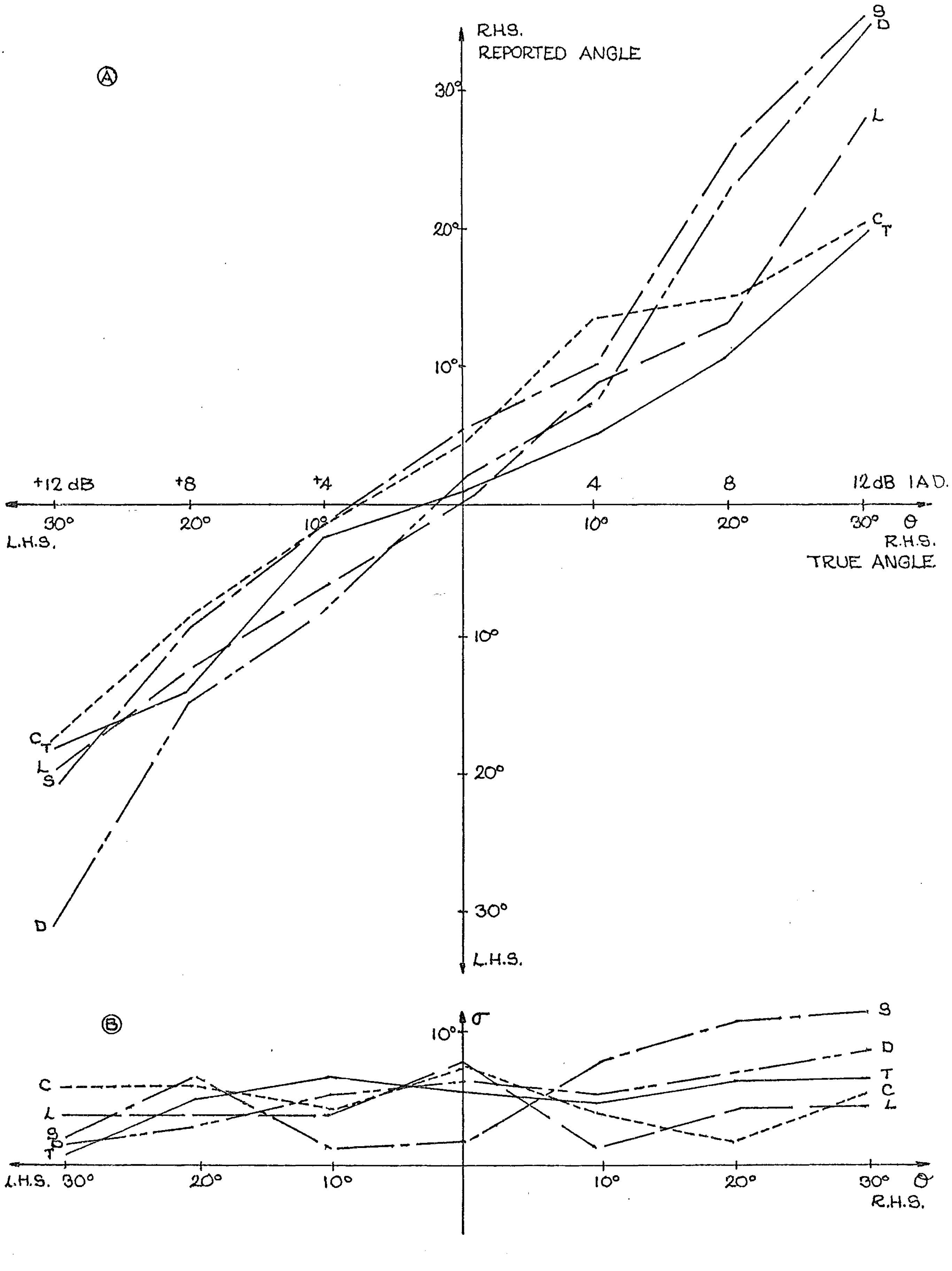
Results

Subjects reported a greater difficulty in lateralizing sound images with ITD and IAD than with IAD alone. One subject (L) reported the images to be behind the head, another subject (D) reported occasions of perceiving two separated images.

The lateralization curves plotted in Fig. 3.15 a show an offset toward the RHS for the auditory image at the centre of the head. Greater variation of reported angles among subjects were found at 10^{o} and 20^{o} on the LHS. The standard deviations are shown in Fig. 3.15 b.

3.5.6 General Discussion and Conclusion

In the IAD experiment, the slopes of some of the lateralization curves varied from 0.6 to 1.2. This suggests that for some subjects, the provided IAD was not adequate, resulting in a constracted auditory space, while for other subjects, the perceived auditory space was expanded compared with real object space. This phenomenon tends to substantiate Rowell's finding (Rowell, 1970) that the lateralization constant varies with individual subjects. On a whole, the rather linear variation of lateralization with respect to IAD tends to support the assumption that:-

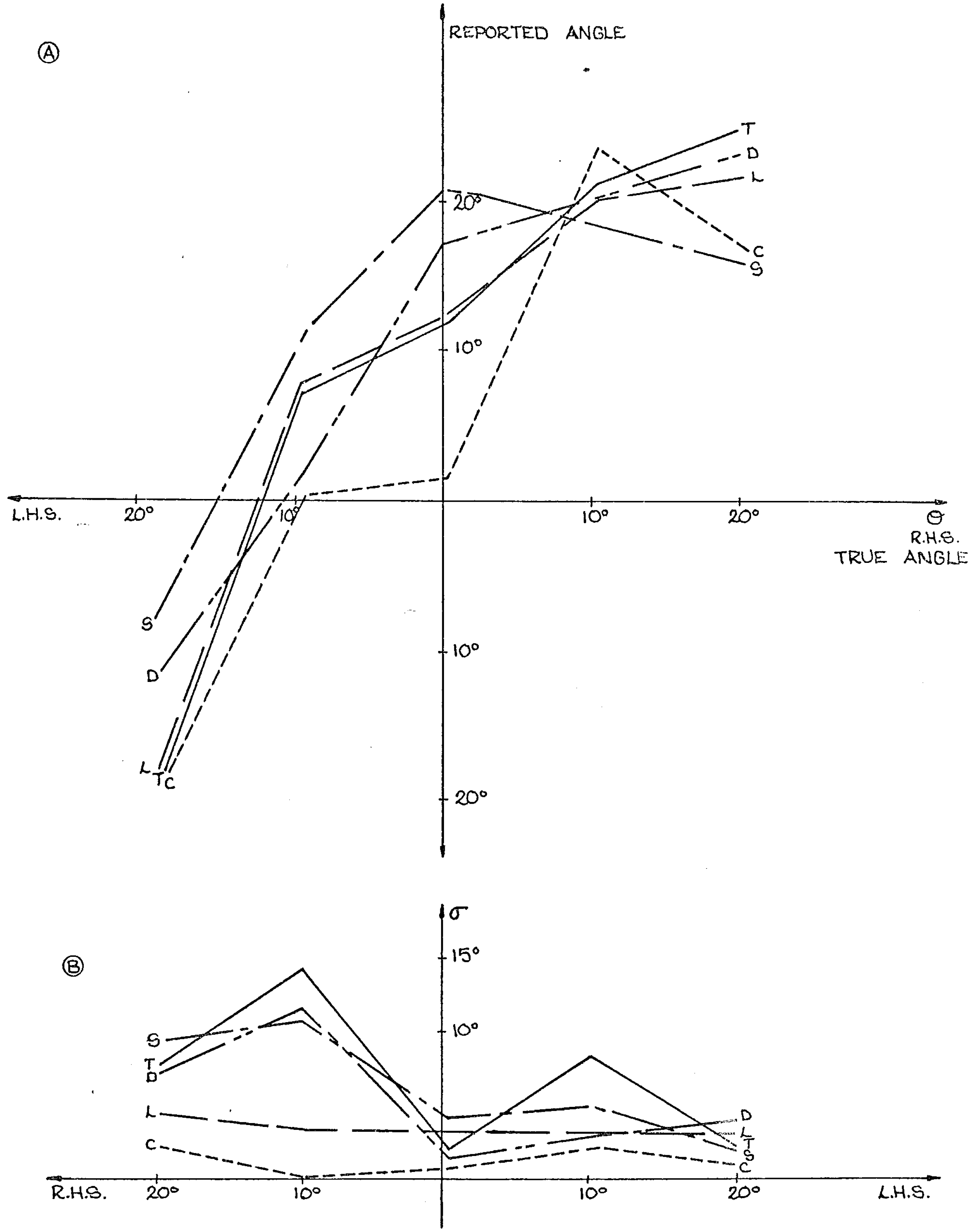


THE USE OF IAD AS THE LATERALIZATION CUE.

Ⓐ REPORTED ANGLES vs TRUE ANGLES.

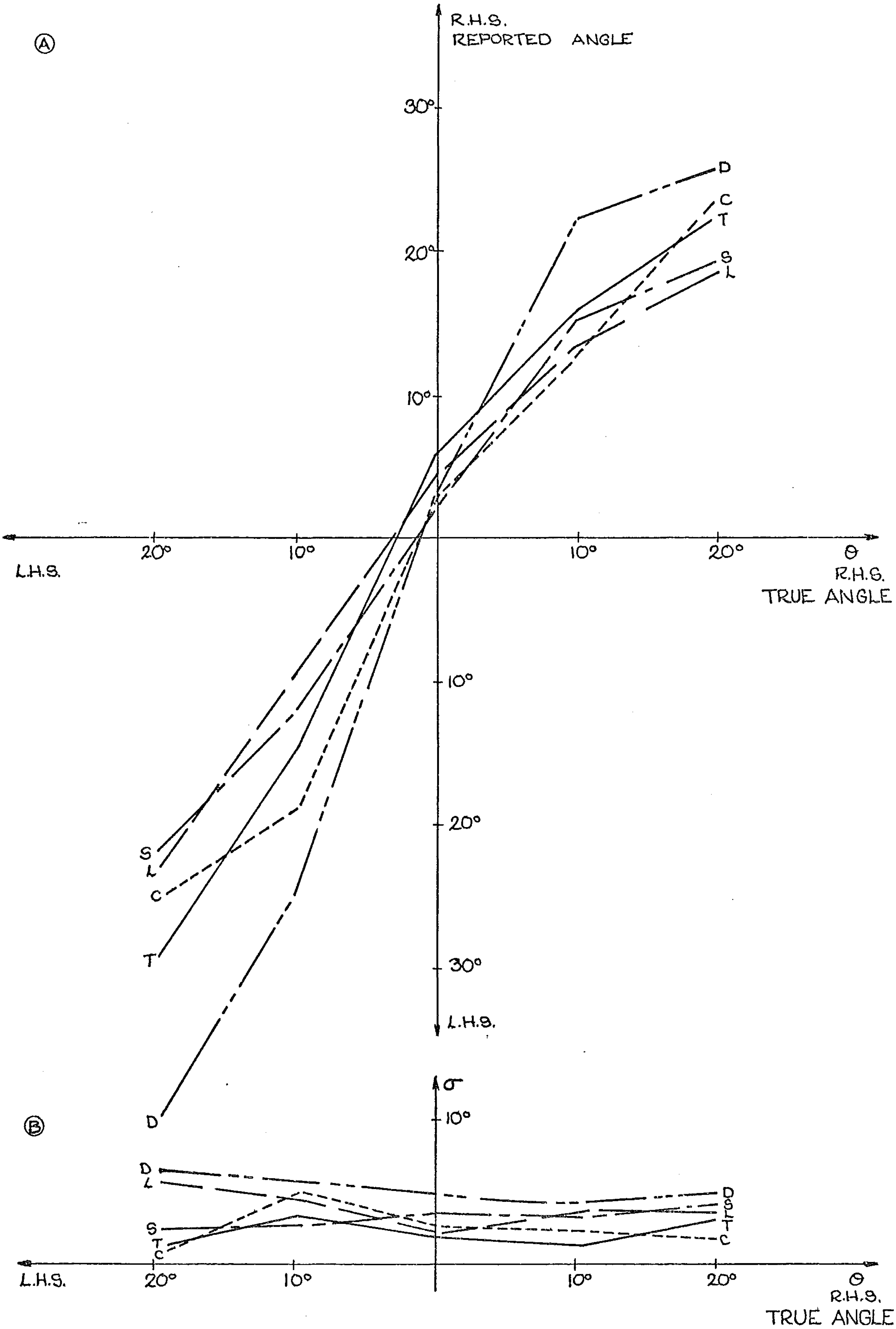
Ⓑ STANDARD DEVIATION.

FIG. 3.13



THE USE OF ITD AS THE LATERALIZATION CUE
Ⓐ REPORTED ANGLES vs TRUE ANGLES
Ⓑ STANDARD DEVIATION

FIG. 3.14



THE USE OF ITD AND IAD AS LATERALIZATION CUES

Ⓐ REPORTED ANGLES vs TRUE ANGLE

Ⓑ STANDARD DEVIATION

FIG. 3.15

$$\Theta = K\log_e \left(\frac{A_1}{A_2}\right) - \Theta_o \qquad \text{(Eq 3.3)}$$

and suggests that mapping of the real azimuth angle to the perceived auditory space is possible with a suitable choice of the splay angle α and the initial offset angle Θ_o.

In the ITD experiment, the relative inaccuracy of the results suggests that the ITD was not reliably given. It is possible that the slow rise time (300 µsec) of the high Q tuned amplifier used in the aid tended to render the small ITD at small azimuth angle (80 µsec for $\Theta = 10^o$) ineffective. Inaccuracies in using ITD as the lateralization cue for clicks filtered by a low pass filter (i.e., slow rise time clicks) have been reported by Teas (1962). He found that as the ITD continuously increased, the image moved out of the median plane then returned to the centre, sometimes even crossing over to the other ear. The successful use of ITD to lateralize clicks in Bekesy (1960) and Guttman (1962) may be attributed to the sharp rise of the unfiltered clicks used.

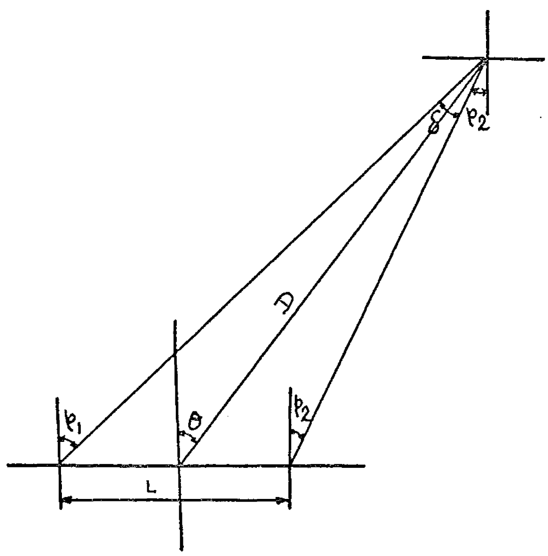
The accuracy in lateralization by a combination of ITD and IAD is comparable with that by IAD alone and superior to lateralization by ITD. However, more difficulties in lateralizing the sound source and occasions of double images were reported. The phenomenon of double images has been reported in the ITD and IAD trading experiments conducted by Withworth and Jeffress (1961) and Hafter and Jeffress (1968). The occurence of double images in this experiment suggested that, at times, the ITD and IAD cues were in conflict. This together with the finding of Teas (1962) as reported above, seems to indicate that again, perception of ITD is not reliable in slow rise time clicks.

The separation of receiving transducers, necessary to provide the required ITD, can also produce erroneous mapping of the real azimuth angles on to the auditory space. It can be seen by considering an object at a distance from the aid as shown in Fig. 3.16: If L is the separation of the receiving transducer, and Θ is the object azimuth angle, then the difference in the reflected angles of the echoes at the two receivers is:-

$$\delta = \psi 1 - \psi 2 \simeq \frac{L\cos \Theta}{D}$$

For directional objects such as hexagonal lamp posts, the target strength can vary widely with reflected angles. Thus it is possible that additional IAD due to the difference in the reflected angles can be introduced into the auditory stimulus and distorts the true object angle. The interference of directional object on the lateralization cue can be greatly reduced by reducing the separation of the transducers.

From the evidences cited above, it was decided to use IAD in the only lateralization cue. The lateralization constant β can be varied simply by altering the splay angle α.



THE DIFFERENCES IN THE REFLECTED BEAM ANGLES AT THE TWO SEPARATED RECEIVERS.

FIG. 3.16

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CHAPTER 4

THE DESIGN OF THE SINGLE OBJECT SENSOR

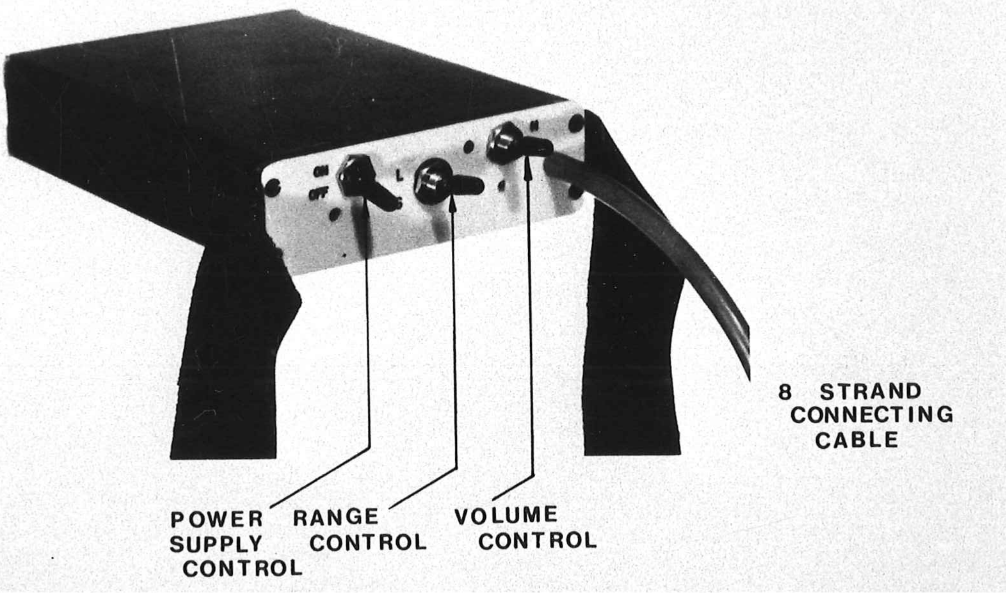
4.1 INTRODUCTION

Most of the blind do not wish to draw other people's attention toward their disability, therefore a mobility aid, especially a head mounted one, should not make a blind person look conspicuous.

The arrangement of the transmitting and receiving transducers on the frontispiece of a spectacle frame as used in the Binaural Sensory Aid, seems to be well accepted by the blind, hence the same arrangement will be used in the Single Object Sensor. This arrangement placed severe constraints on the design of the aid and strongly affects the size and the mounting of the aid components. With conventional electronic construction technique, it was not possible to fit all the aid components into the spectacle without making it conspicuously large and unattractive. Thus, only the transmitter, the receivers and their associated pre-amplification were mounted on the frontispiece of the SOS spectacle. Two sub-minature earphones (Knowles BJ 1590) were mounted in the spectacle arms to provide the auditory stimulus.

The rest of the electronic circuitry and the power supply were mounted in a small control box (11.5 cm x 9 cm x 2.5 cm) connected to the spectacle frame by an 8 strand cable. There are three toggle switches on the control box. One is the ON-OFF switch, one is used to select the range (short range of 2.5m or long range of 5 m), the other switch is used to provide


RECEIVER
TRANSMITTER
MINIATURE EARPHONE & EARTUBE


8 STRAND CONNECTING CABLE
POWER SUPPLY CONTROL
RANGE CONTROL
VOLUME CONTROL

a 10 dB change in sound intensity.

Toggle switch is used to control loudness instead of the conventional rotary one because the control box is usually worn underneath clothing which renders rotating controls difficult to operate. The toggle switches can be simply operated directly through garments. The low level of loudness was set at 55 dBa (with the object being a 2.5 cm dia. wooden pole at 2.5 m distance) although it can be changed internally to suit individuals.

As mentioned in Chapter 2, the requirements of a mobility aid have not been clearly established, therefore some of the parameters in the SOS could only be tentatively chosen, mostly based on those of the BSA. One of the parameters was the beam width of the illuminating field of the aid. The horizontal 6 dB beam width was chosen to be $\Theta_H = 45^\circ$, the medium beam width value of the BSA which varies from 60° to 30° during a frequency sweep. The range of the aid has also been tentatively chosen to be 3 m. However, experiences with an experimental model SOS indicated that a longer range could be of more benefit to a user in an uncrowded environment. Therefore it was decided to have two range settings 2.5m and 5 m. The range setting can be selected by means of a toggle switch as mentioned earlier.

Other parameters of the aid, such as the transmitting frequency, the size of the transducers are related to the beam width of the aid and will be discussed in Section 4.2.1 and 4.2.2. These parameters, in turn influence the transmitting power and hence the size of the minimum detectable object as will be seen in Section 4.2.3.

The operation of the aid circuitry is described in Section 4.3.1. The designs of some of the circuits considered to be novel are briefly described in Section 4.3.3.

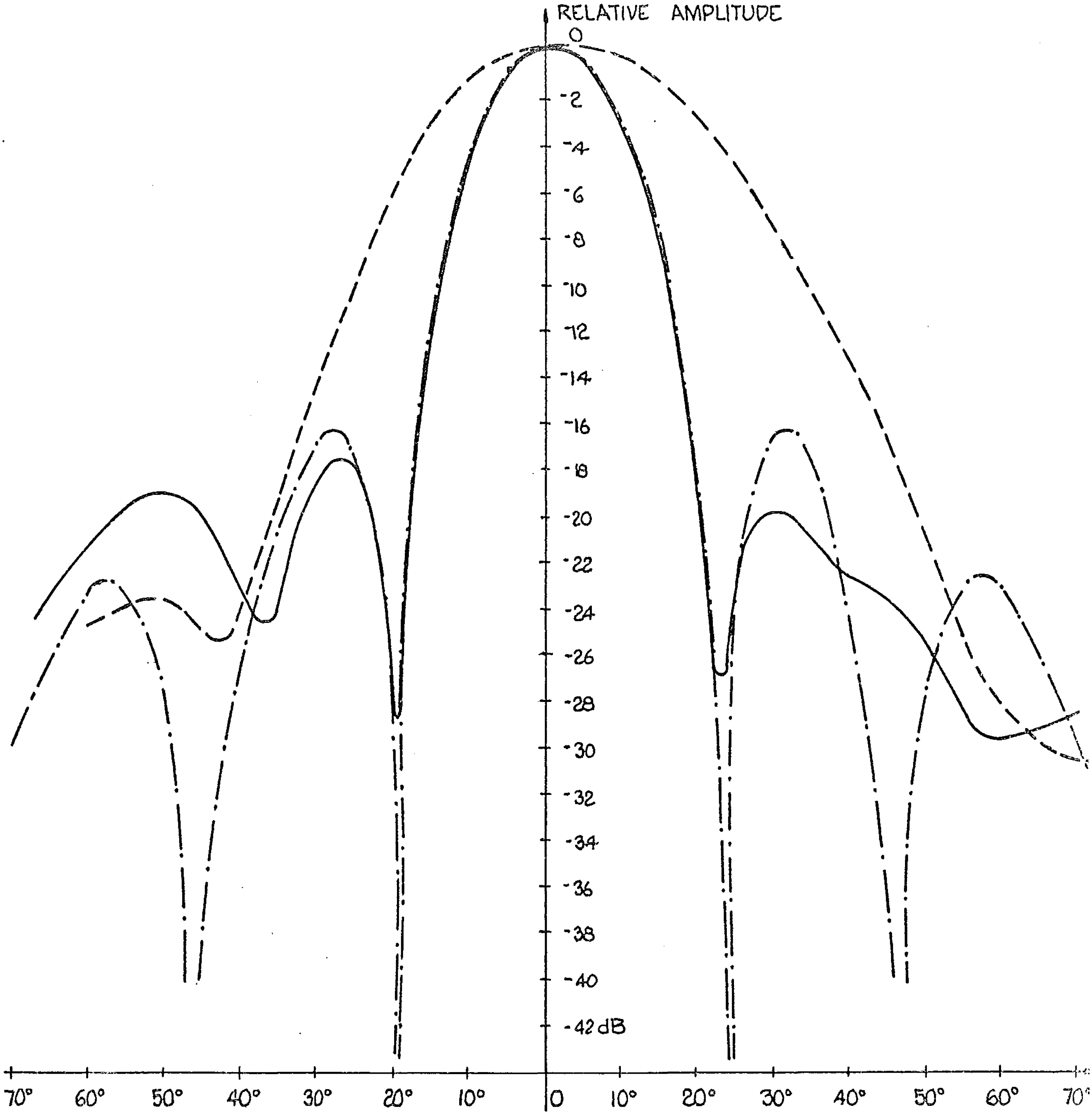
It is worth noting here that the SOS was designed such that its audio display remains completely silent until an object is detected.

4.2 THE POWER CONSIDERATION

4.2.1 Vertical Beam Width of the Transmitting Transducer

Solid dielectric electrostatic transducers of circular shape were originally used in an experimental model of the SOS to give equal vertical and horizontal beam width for the illuminating field of the aid. However, they were found to produce an undesirable effect: Since the aid can only detect one object at a time, with a wide vertical beam width, the aid may "lock" on an overhanging object high above a user (for example, overhanging shop neon signs) and ignore an object in front of him. The latter, although at a greater distance than the overhanging neon sign, could be of more interest to the user. Tilting the transmitter downward could reduce the incidence of the aid being "locked" on a high overhanging object, however, the probability of getting echoes from the ground is also greatly increased.

It was therefore decided to use a smaller vertical beam width. A value of $\Theta_H = 22^{\circ}5$ was tentatively chosen, being half of the horizontal beam width. Techniques were then developed by the technical staff of this Department to produce oval shaped solid dielectric electrostatic transducers; great efforts were made to insure that the transducer sensitivity was maximised at



THE TRANSMITTER DIRECTIONAL PATTERNS.

FIG. 4.1

THE TRANSMITTING AND RECEIVING TRANSDUCERS. FIG. 4.2

The operating frequency was chosen to be 80 kHz. The theoretical directivity of the transducer is also shown in Fig. 4.1.

4.2.3 The Minimum Detectable Object

The sonar cross section σ of the minimum detectable object is given by (see Appendix 2, the Sonar Equation, for detailed derivations).

$$\sigma = \frac{S_{min}^2 \times 4 \quad D^4 \times \pi \quad \times 10^{(2\alpha D + Et - Er)/10}}{e_t^2 \times R \times D F} \qquad (4.1)$$

where Smin = the minimum detectable voltage at the receiver.

D = object distance.

α = attenuation constant of sound in the air.

E_t, E_r = transmitter and receiver sensitivity co-efficients.

e_t = transmitting voltage.

R = reflectivity of target.

DF = directivity of the transducer.

Some of these factors are briefly discussed in the following sections, and a typical set of values will be substituted into Eq. 4.1 to determine the minimum size of the detectable object.

(i) The Minimum Detectable Voltage at the Receiver

The ability to detect a signal in a sonar receiver is limited by the noise occupying the same frequency band as the signal. The signal to noise ratio for an average false alarm time Tf_a is given by (see Appendix 3; the noise was considered to be of Gaussian distribution).

$$\frac{S}{N} = \frac{S_{min}}{\Psi_o^{\frac{1}{2}}} = \frac{V_T}{\Psi_o^{\frac{1}{2}}} = 2 \ln \left(\frac{1}{B_{BP} \times T_{fa}}\right)^{\frac{1}{2}}$$

where V_T = the threshold of detection voltage

B_{BP} = band width of band-pass amplifier

= 1800 Hz (from the Doppler shift consideration, Section 4.3.3. iv)

Taking $T_{fa} \geq 2.5$ minutes. Fig. 1 in Appendix 3 gives

$$\frac{S_{min}}{\Psi_o^{\frac{1}{2}}} \geq 5$$

At the maximum range where the gain of the system is highest (see Section 4.3.3 (ii)), the equivalent noise level at the input of the receiving transducer was measured at 12 μV. Thus a minimum voltage of $S_{min} \approx 62.5\mu V$ is required to provide an average false alarm time of 2.5 minutes.

(ii) <u>The Transducer sensitivity co-efficients</u>

The transducer sensitivity co-efficients are determined from:-

$$e_t = P_t 10^{(Et/20)} \text{ for transmitter}$$

$$e_r = P_r 10^{(Er/20)} \text{ for receiver}$$

where e_t = the voltage applied to the transmitter in volts

e_r = the voltage output of the receiver in volts

P_t = the sound pressure level at 1 m from the transmitter in μ bar

P_r = the sound pressure level at the position of the receiver in μ bar

E_t/E_r = the transmitter/receiver sensitivity co-efficient in dB ref 1V/μ bar.

Existing transducer technology limits the maximum voltage which can be applied to the transmitter to 200 V peak to peak (p-p). The sensitivities of the transducers were found to be (See Appendix 4, The Transducer Sensitivity, for detailed measurements).

E_t = 0.1 dB ref. 1V/μ bar

E_r = -69.10 dB ref. 1V/μ bar

(iii) A Typical Example

Consider a metal sphere at the maximum range of 5m as the target, we have the following typical set of values:-

Smin = 62.5×10^{-6} V

D = 5 m

α = 1.5 dB/m at 80 kHz

E_t = .1 dB ref. 1V/μ bar

E_r = -69.1 dB ref. 1V/μ bar

e_t = 200V p.p. = 71V RMS

R = 1 for hard surface

$$DF = \frac{4\pi}{\Theta_V \times \Theta_H} = \frac{4\pi}{0.39 \times 0.78} = 41.3$$

The sonar cross section of the minimum detectable object, σ, is given by: (Eq. 4.1).

$$10 \log_{10}\sigma = 20 \log_{10} S_{min} + 10 \log_{10} 4\pi + 40 \log_{10} D + 2\alpha D + E_t - E_r - 20 \log_{10} e_t - 10 \log_{10} R - 10 \log_{10} DF \quad (4.2)$$

$$= -84.08 + 10.99 + 27.96 + 15 + 0.1 + 69.1 - 37.02 - 0.0 - 16.15$$

$$= -14.10 \text{ dB}$$

hence $\sigma = 0.039\ m^2$

The sonar cross section (sphere) is given by

$$\sigma = \pi a^2 \quad (4.3)$$

where a is the radius of the sphere

Thus $a = 0.11$ m

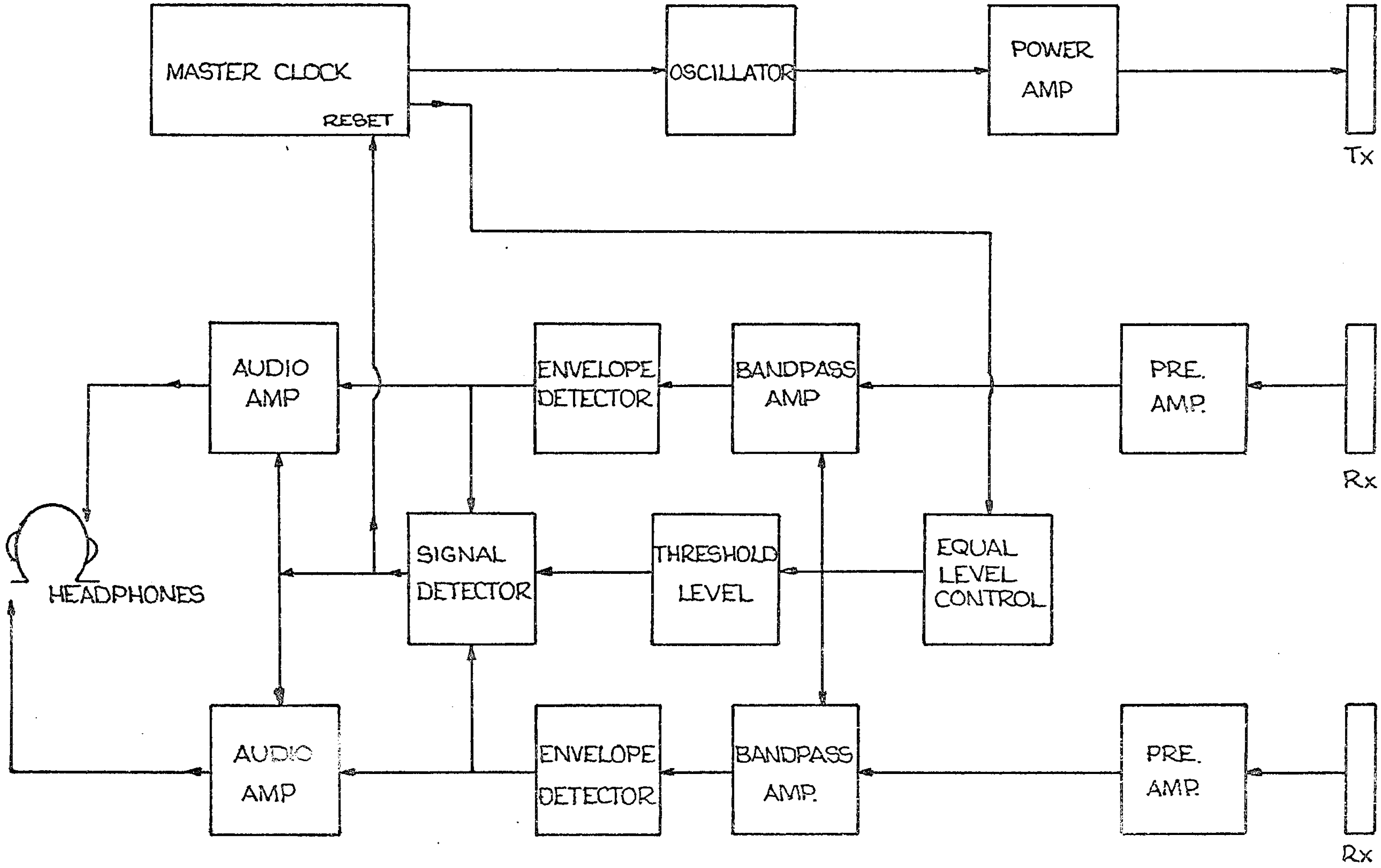
In practice a copper sphere of 0.125 m radius is detected at 4 m.

4.3 THE SYSTEM DESIGN

4.3.1 General Description

A block diagram of the system is shown in Fig. 4.3. The master clock controls the oscillator to produce a burst of 80 kHz for 1 msec in every 16 msec (for a 2.5 m range). This ultrasonic signal is amplified by a power amplifier and transmitted via the transmitting transducer (Tx). Reflected signals from objects are amplified by the pre-amplifier and the band-pass amplifier, and modified by the equal level control network before being rectified by the envelope detector. Two events can then happen:-

(i) If the signal is above a preset threshold level, it will be passed through to the audio amplifier and then presented to the user. At the same time, a trigger pulse is sent to the master clock to reset the clock in order to produce another burst of ultrasonic signal.



THE SINGLE OBJECT SENSOR BLOCK DIAGRAM.

FIG. 4.3

(ii) If the signal is below the threshold level, no audible signal will be presented to the user. A burst of ultrasonic signal will be transmitted automatically 16 msec (for a 2.5 m range) after the last burst was transmitted.

The function of most system blocks are self-explanatory, except the equal level control network which will be described in more details below:-

4.3.2 <u>The Equal Level Control Network</u>

As mentioned in Section 3.2, a time-varying-gain amplifier is required to modify the echo amplitudes such that they are of the same intensity regardless of distance. The aim was to reduce the false triggering due to the multiplicity of objects in space. An added advantage of this scheme is reduction of the extreme variation in loudness of sounds representing objects at the closest and the farthest range. (The power of an echo theoretically decreases inversely with the fourth power of distance or 12dB per doubling distance).

The modification is achieved by the use of an equal level control network. The network provides a much higher gain for signals of far distance objects than for those at shorter distance. The exact level of gain as a function of distance will be discussed in Section 4.3.3 (ii). The network also controls the threshold level circuit to provide a threshold level proportional to the gain of the system. The threshold level is useful in preventing noise at the end of a transmitting cycle (where noise level is at maximum due to the increase in gain with distance) from passing through to the audio stage and false triggering the transmitter. This arrangement insures that the aid produces no audible sound when no object is detected

4.3.3 The Design of Some of the System Circuits

Since the device has to be carried by a blind person, size, power consumption and minimizing the number of controls, are the main factors influencing the design of the electronic circuitry. The system is powered by a rechargeable 12V Ni-Cd battery (Varta 150 DK) with the capacity of 0.15 AHr. The aim of the design was to restrict the power consumption to about 30-50 mA so that the aid can be used continuously for 3 - 5 hours. Hence, whenever possible, analogue circuits were replaced by digital ones to take advantage of the low current consumption characteristic of CMOS.

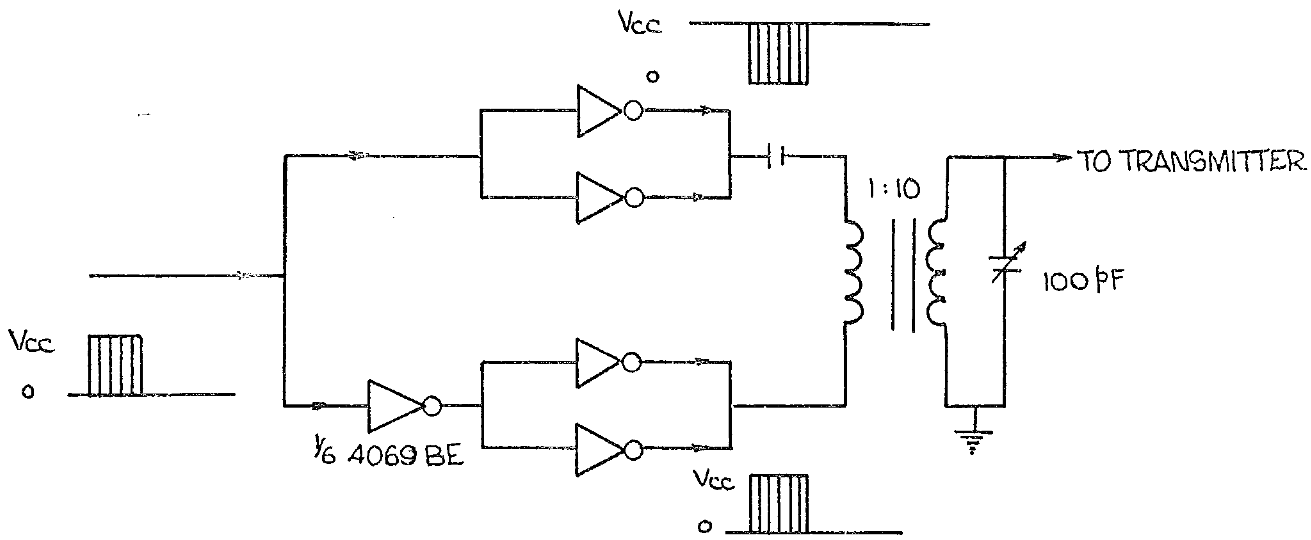
Some of the circuit designs considered to be novel are briefly described below. Conventional circuit designs and the complete circuit diagram of the aid are presented in Appendix 5.

(i) The Transmitter Power Amplifier

B type CMOS Inverters (RCA 4069 BE) driven in a push-pull fashion as shown in Fig. 4.4 were used as the power amplifier. A pair of inverters was used in each mode to provide the required power output. A step up transformer with a turns ratio of 10:1 was used to increase the peak to peak output voltage to 200 V.

(ii) The Equal Level Control Circuitry

In normal use, most of the objects will be in the far field of the transmitter. The theoretical spreading loss therefore varies as the fourth power of object distance. This, coupled with the absorption loss of the ultrasonic signal in



THE TRANSMITTER POWER AMP.

FIG. 4.4

the air at 1.5-3 dB/m (Sivian 1947, Martin 1969), requires a compensation function of the form $at^4 + bt$

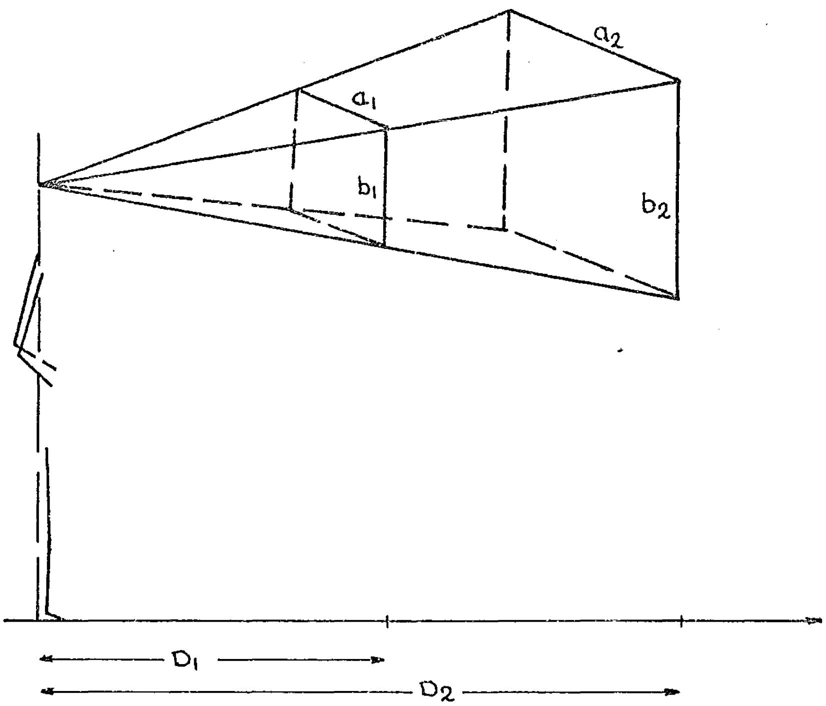
$$(t = \text{time})$$

to provide the echoes with equal amplitudes, regardless of distances.

However, experimental results showed that for most objects in the environment, the loss in signal intensity varies at a much lower rate than $at^4 + bt$. This is because objects in the environment are not completely submerged in the illuminating field of the transmitter. The sonar cross section, σ, of such objects as lamp posts, telephone boxes, street sign posts, traffic posts, increases as the object distance D increases as shown in Fig. 4.5. Therefore while the loss is increased by $at^4 + bt$, the illuminated area increases by bD^2 which corresponds to an increase in the echo strength of ct^2. The intensity variation with distance of a metal pole of 2.5 cm diameter is shown in Fig. 4.6.

Compensation for the loss in the form $at^4 - ct^2 - bt$, while not easily realised by RC, LC or diode shaping networks, can be conveniently formed by a stepwise shaping function from a digital network as shown below (Fig. 4.8).

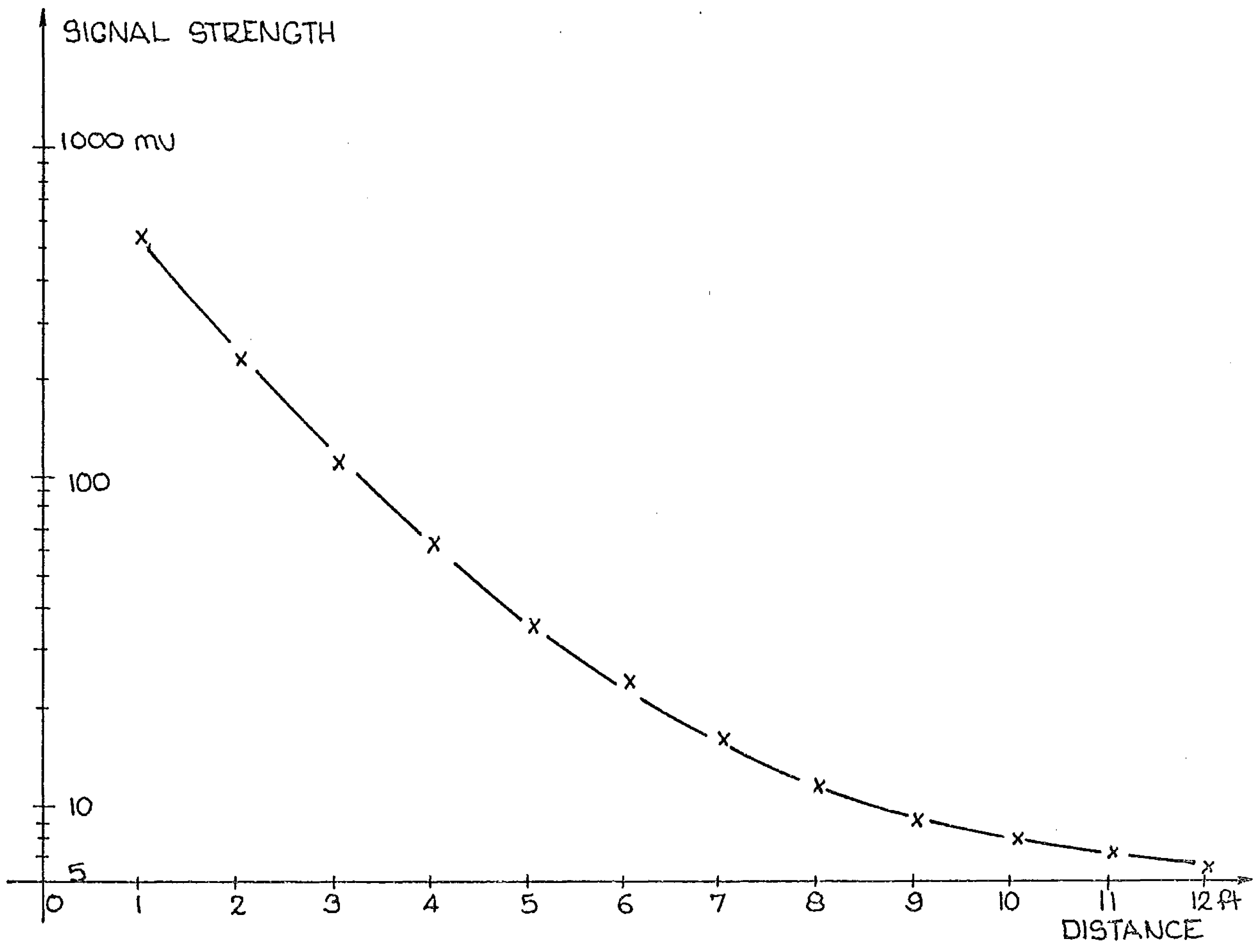
In this circuit, the output of the master clock is decoded by a multiplexer to produce a sequence of high levels at its 16 outputs (for the 5m range; or at its 8 outputs for the 2.5m range). Each output maintains the high level for 2 msec. Resistors R1 - R16 at the outputs of the multiplexer outputs to form the required shaping function. The shaping function can be easily changed, by altering the values of resistors R1 - R16,



THE INCREASE IN OBJECT AREA WITH DISTANCE.

$$\frac{a_2}{a_1} = \frac{b_2}{b_1} = \frac{d_2}{d_1}$$

FIG. 4.5



VARIATION IN SIGNAL STRENGTH OF A METAL POLE WITH DISTANCE

FIG. 4.6

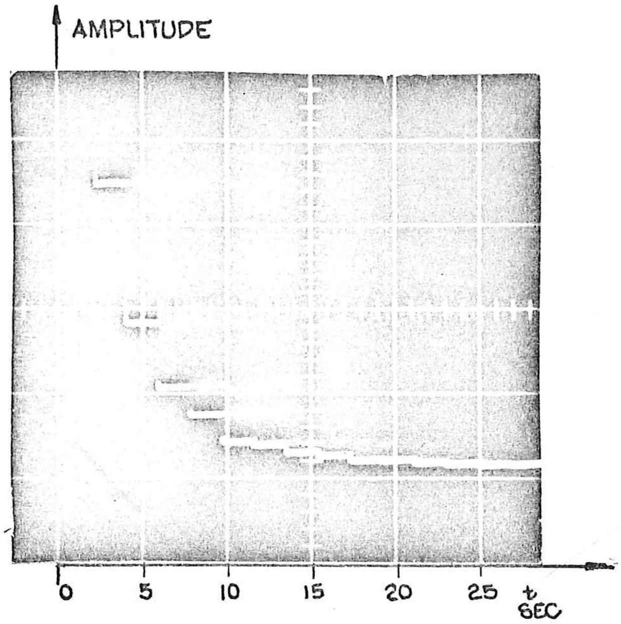
to produce any required echo amplitude profile. This is of particular advantage, especially if the variation of natural loudness with distance is to be incorporated into the device auditory display to provide an extra distance cue as will be discussed later in the thesis. A typical shaping function is showed in Fig. 4.7.

The amplitude profile controls the amplitude of the echoes by means of a transistor Q1, acting as an attenuator. With a BC 107 transistor, an 80 dB attenuation can be realised. The extremely low current consumption ($I < 1 mA$) of the transistor attenuator (compared with I = 10 mA for a typical 4 quad. multiplier, for example XR 2208) makes it an attractive choice. The Equal Level Control network is shown in Fig. 4.8.

The variation of the attenuator output as a function of the control current is shown in Fig. 4.9.

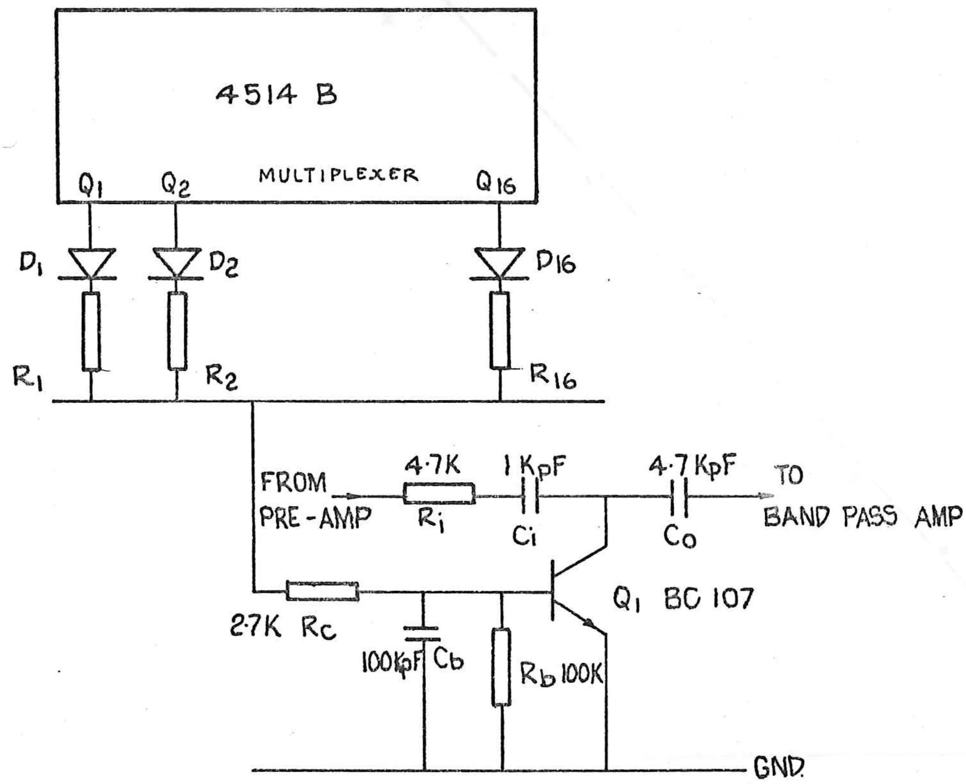
The Pre-Amplifier

The pre-amplifier was mounted in the frontispiece, immediately behind the receiving transducer to reduce the length of the connecting cable, and hence the picked-up noise. Size and ease of mechanical construction, thus, are the important factors influencing the final design. In the aid, the dual ultra-low noise op. amp. LM 381A (typical total equivalent input noise specified by the manufacturer as 0.5 μV RMS) was used in the single ended mode to minimize the noise. Only three resistors and a capacitor were necessary to control the amplifier gain and the low frequency cut-off. The components were built around the dual-in-line package. The pre-amplifier had a gain of 250. The actual noise level was measured to be 1 μV RMS. The circuit diagram is shown in Appendix 5.



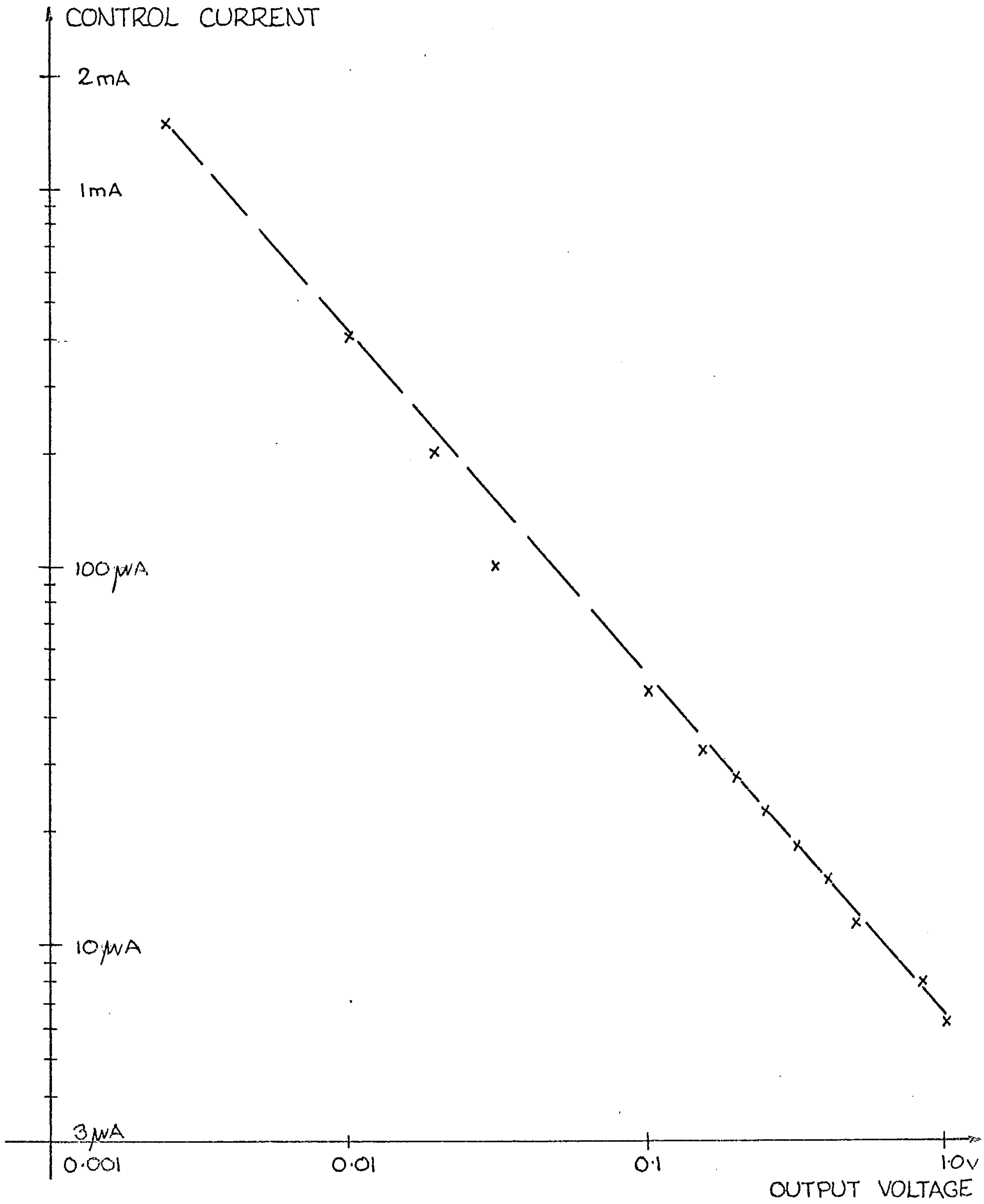
A TYPICAL SHAPING FUNCTION

FIG. 4.7



THE EQUAL LEVEL CONTROL NETWORK.

FIG. 4.8



THE VARIATION OF OUTPUT VOLTAGE WITH CONTROL CURRENT OF A TRANSISTOR ATTENUATOR

FIG. 4.9

The Band Pass Amplifier

At the output of the pre-amp, the echo from a metal pole of 0.025 m diameter at 4 m was found to be 2 mV p.p. and the noise level was about 1.8 mV peak. To detect such signal, a high Q band pass amplifier was required. The maximum acceptable Q is dictated by the Doppler shift of the propagating frequency due to the movement of a user: If V_r is the relative velocity between the user and an object, the maximum Doppler frequency shift is given by

$$fd = fo \times \frac{2V_r}{c}$$

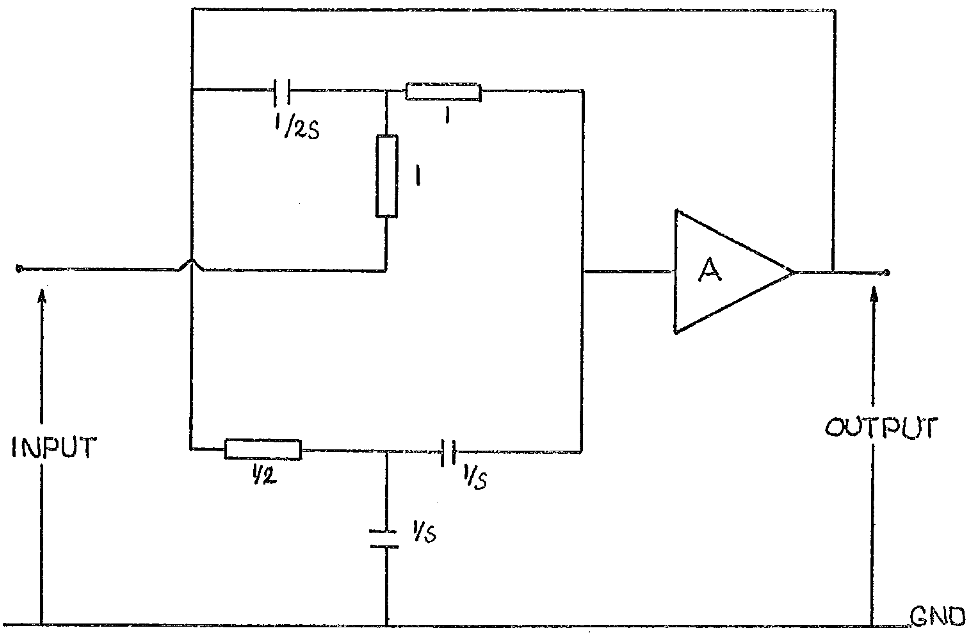
If $V_r = 4$ m/s, maximum relative speed of the user and a pedestrian moving toward each other, then fd = 1865 Hz. Hence the maximum Q was taken to be: Q = 40.

A high Q band pass amplifier, as shown in Fig. 4.10, was used. The amplifier transfer function is given by (Selly, 1968):

$$T\ (s) = \frac{1}{S^2 + 4\ (1-A)\ S + 1}$$

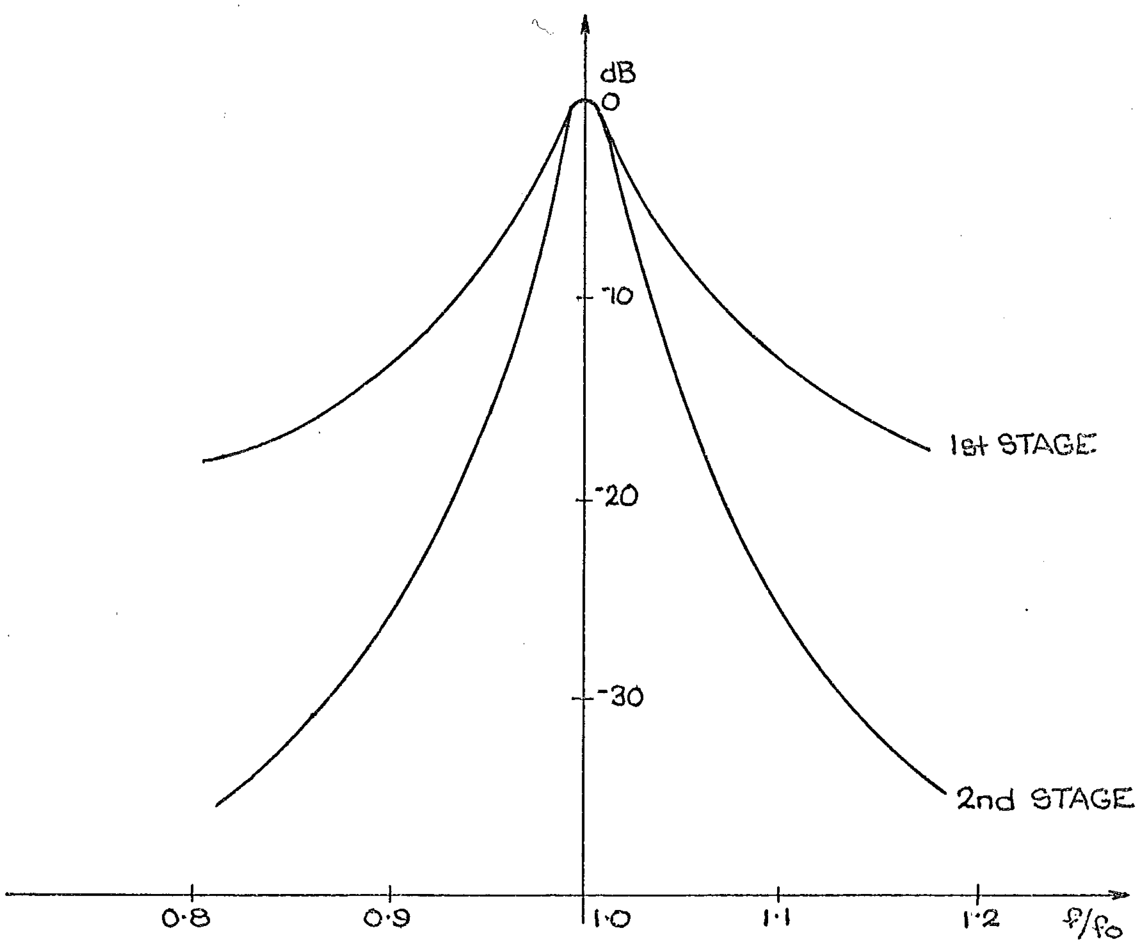
When the gain of the amplifier is set at A = 1, an infinite Q amplifier is achieved, due to the fact that only zero-axis poles exist. However, limitations in the amplifier and the matching of components reduce the Q of the amplifier considerably. With 1% tolerance in the component values and using a 741 Op. Amp. as the amplifier, a Q = 40 could be obtained. The frequency response of the band pass amplifier is shown in Fig. 4.11.

To improve signal perception without reducing the band width, two stages of band pass amplifier were cascaded to provide a sharper cut off outside the pass band (-12 dB at 1.1 fo, as shown in Fig. 4.11).



AN INFINITE Q AMPLIFIER (A=1)

FIG. 4.10



THE FREQUENCY RESPONSE OF THE TUNED-AMP.

FIG. 4.11

Because the band pass amplifier has high input impedance and positive gain, capacitive coupling between the two stages could cause oscillation. To prevent it from occurring, an inverter was used between the two cascaded band pass amplfiers as shown in Appendix 5.

4.4 CONCLUSION

Preliminary impressions from the mobility teachers and experienced B.S.A. users indicated that the device beam width was adequate for mobility in suburban areas. The size and the appearance of the device were also well accepted by the people concerned (Kay, Bui, Brabyn and Strelow, 1977).

The device has been used extensively for more than two years and has proven to be reliable within the temperature of 1° - 28°C. Under laboratory conditons, the working temperature range was found to be 0° - 60°C. The transmitting frequency and the centre frequency of the band pass amplifier normalised to the values at 20°C are shown in Table 4.1 as function of the environment temperature. The transmitting frequency fo at 20°C is: fo = 80032 Hz.

Table 4.1 Variation of Transmitting Frequency and Band Pass Amplifier Centre Frequency with Temperature

Temp.	Transmitting Freq. fo	Band Pass Centre Frequency fo
0°	100.72%	100.68%
20°C	100%	100%
60°C	99.5%	98.5%

The total current consumption for the complete Single Object Sensor at the supply voltage of 12V is 30 mA. With the battery used (Varta 150 DK), 5 hrs continuous running can be obtained from a fully charged battery.

While the emphasis was on the performance of the device so that the feasibility of a Single Object Sensor as a mobility aid could be studied, the replacement of most of the analogue circuits by their digital equivalents and the use of conventional and readily available components enhance the ease of assembling the device, and make it feasible for commercial reproduction.

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CHAPTER 5

ON THE ROLE OF PINNA IN AUDITORY LOCALIZATION AND THE EFFECT OF EXTERNALIZING A SOUND SOURCE IN THE CONTROL OF LOCOMOTION WITH THE SINGLE OBJECT SENSOR

5.1 INTRODUCTION

This chapter returns to the problem of externalizing a sound image, and considers the effects on the control of locomotion when the listening condition was changed from dichotic to free field.

As mentioned earlier, a dichotically-presented sound is heard as "inside" the head (lateralization) and a sound presented via a loud-speaker in space (free field) is heard as "out there" (localization). The literature on the likely mechanisms differentiating lateralization and localization is reviewed in the first section of this chapter. A majority of the literature suggested that the transformation of a sound by the pinnae is the most likely factor. A series of experiments was designed to test this hypothesis. It involves the study of the "in head" and "out there" sensation when the pinnae were rendered ineffective as well as the effect on localization when the pinnae were reversed so to be pointed backward.

In the second section, the control of locomotion in a mobility laboratory under both the dichotic and the free field listening conditions was compared. Approaching a target was chosen as the control task and a computer-simulated Single Object Sensor was used to provide the spatial information.

Conclusion as to the mechanism to be used in the SOS is given in the final section of the chapter.

5.2 LOCALIZATION AND LATERALIZATION: A LITERATURE REVIEW

The differences between localization and lateralization can be attributed to factors which exist in the free field but not in the headphones listening condition. They are: visual information about the external sound source, amplitude differences between the direct and reverberated sound in a room, effect of head movement, bone conduction, and the modification of sound by the pinnae. Literature on the effects of these factors on lateralization and localization is briefly reviewed below.

5.2.1 Visual information about the external source

There is evidence that visual information could influence auditory localization.

Thurlow and Kerr (1970) found that the rotation of a striped visual environment around a subject caused displacement of the perceived localization of a sound source toward the direction of the rotation.

Cohen (1974) found that auditory localization changed after prismatic exposure under continuous and terminal visual feedback. He believed that the interaural transfer of the prism after-effects was due to the change in the sensed position of the head relative to the trunk of the body. Under normal visual condition, auditory localization was found to be more accurate with than without vision (Warren, 1970). This finding seems to be substantiated by the findings of Jones and Kabanoff (1975) who argued that the auditory position was initially given from aural cues; visual information was then used to stabilize and update the auditory position's memory. However, it does not follow that an external sound is heard as inside the head when a listener is blindfolded. Accuracy in sound localization without vision does not deteriorate either: Blindfolded subjects, when asked to specify the position of a sound source in one of the eight possible positions, produced almost 100% correct responses, under free head movement conditon. (Fisher and Freedman, 1968).

Therefore, visual information does not seem to be an important factor in differentiating localization and lateralization.

5.2.2 Amplitude differences between the direct and the reverbereated sounds

The acoustic energy density ratio of the reflected sound to the direct sound (AR) was considered by Sakamoto, Gotoh, and Kimura (1976) to be one of the most important factors that provide the "out there" sensation in hearing.

In their experiments with sound recorded through an artificial head and presented through a pair of headphones, they found that:

(a) The percentage of "out of head localization" was very low when sound was recorded with the artificial head in an anechoic room.

(b) When the recorded sound was mixed with a similar sound recorded in a sound diffused room, the sound image moved toward the forehead direction with increasing AR.

When AR was sufficiently large (AR = 2 or 3), the sound was heard as outside the head, a little above the horizon in the median plane.

Although a sound, with sufficiently large AR, may have been heard as outside the head when listened to through a pair of headphones, it may not follow that AR is the most important factor differentiating localization and lateralization because, in free field condition, a sound is always heard as outside the head, even in an anechoic room where AR is negligible.

5.2.3 Effect of head movement on auditory localization

Localization was found to be more accurate under free head movement than under restricted head movement conditon, especially when the subject's pinnae were rendered ineffective (Fisher and Freedman, 1968).

This finding seems to substantiate the analysis undertaken by Mills (1972) who argued that the ears can be considered as a pair of holes separated by a spherical obstacle (the head). If the head is stationary, the source of sound producing a certain interaural time difference (one of the cues used in auditory lateralization) could be anywhere on a conical surface, called the cone of confusion (Fig. 5.1).

The cone of confusion is determined by:

$$\text{cone surface} = \frac{2r}{c} \sin\theta \sin\varepsilon$$

where: r = radius of the head

c = velocity of sound in the air

θ = azimuth angle

ε = elevation angle

Therefore, under restricted head movement condition, localization can be inaccurate. When the head is moving, however, the relative rate of change of the interaural time differences uniquely specifies the azimuth angle of the sound source, and localization accuracy should improve.

Other authors, however, argued that while the movement of a pair of holes separated by a spherical obstacle could bring a sound source into focus; the ears and the head are not a simple pair of holes separated by a sphere. Factors, other than head movement, such as the shadows cast by the pinnae and the bone conduction by the skull could be responsible for auditory localization.

5.2.4 Effect of bone conduction on auditory localization

Sone, Ebata and Nimura studied the role of bone conduction in sound localization in 1968 (Sone et al., 1968). In one of their experiments, a sound was presented to the subject through two independent channels; bone conduction due to vibration of the skull in a sound field, and headphones. When the bone-conducted sound was louder than the same sound presented simultaneously through headphones, the sound image was reported to be shifted forward and the sound was heard as "out there". When the bone-conducted sound was removed, the sound was heard as inside, at the back, of the head.

In another experiment, the subject was asked to specify the direction of a sound source presented randomly in front or at their back. With restricted head movement, the accuracy of the results improved as the sound intensity was increased from below bone conduction threshold level, to about 80dB. The results are reproduced in fig. 5.2.

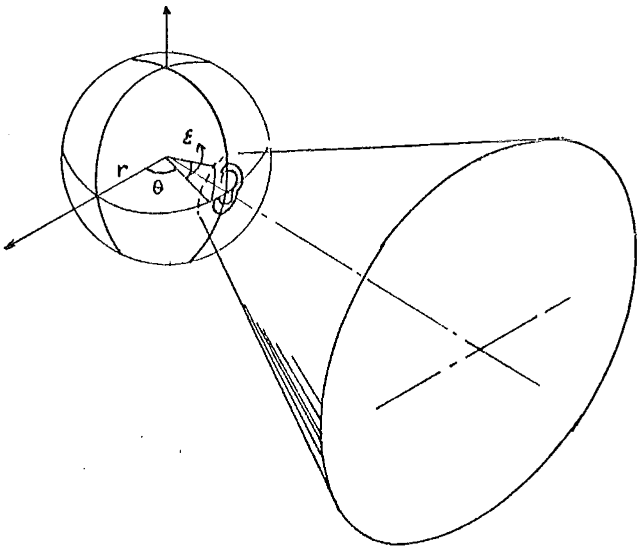
Sone argued that, since the percentage of the correct judgement improved with increased sound pressure level above the bone conduction threshold level, bone-conducted sound is the most probable factor influencing the sound localization.

While Sone's results indicated a 100% correct response for sound at 80dB SPL, the percentage of correct responses below bone conduction threshold, (which is about 60dB above air conduction threshold; Bekesy, 1948) is about 70% -90%. This indicates that bone conduction may not be the only factor responsible for correct auditory localization.

5.2.5 Effect of pinnae on auditory localization

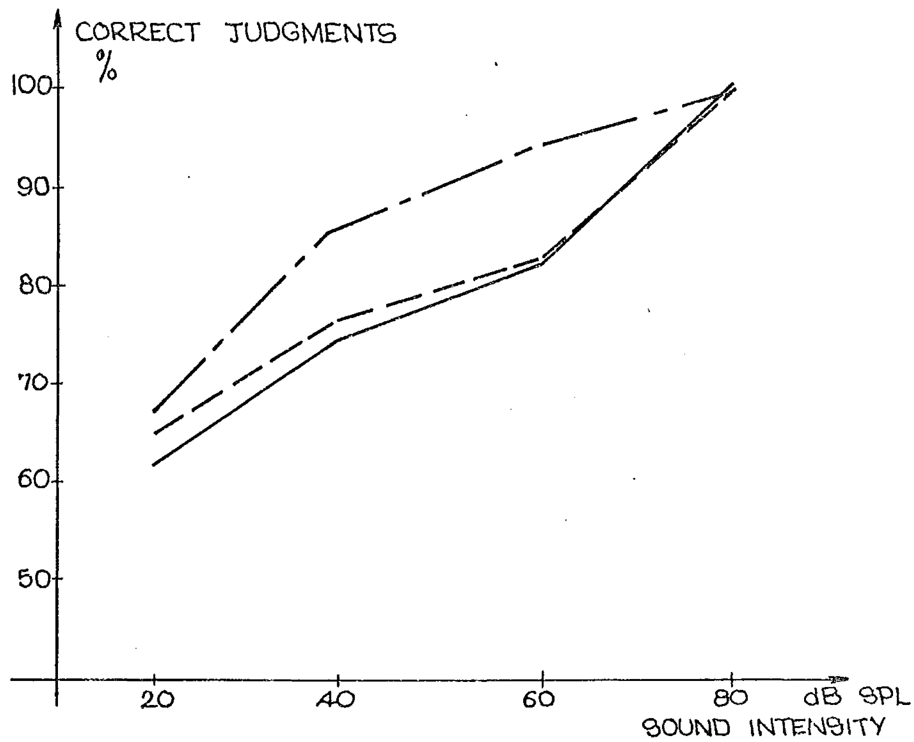
The role of the pinnae in sound localization has been noted for more than a century, but it is not until 1959 when McLean (Batteau, 1967) demonstrated that distortion of the pinnae changed the perception of the location of a sound source, that researchers started to concentrate on the effect of pinnae in auditory localization.

Physiologically, the importance of the pinnae seemed to be tentatively substantiated by the work done by Flynn and Elliott (1965) who found that, in cats, removal of the pinnae resulted in a significant loss of hearing, especially at high frequencies. They speculated that it was reasonable to expect the pinnae to perform some useful function since the thresholds of hearing were better with, than without the pinnae.



A CONE OF CONFUSION FOR
A SPHERICAL HEAD (MILLS, 1972)

FIG. 5.1



SONE et al. (1968) AUDITORY LOCALIZATION AS A FUNCTION OF SOUND INTENSITY.

FIG. 5. 2

Behaviourally, the role of pinnae in auditory localization has been examined by Fisher and Freedman (1968), who found that under restricted head movement condition, localization was better with pinnae than with pinnae obstructed. Even artificial pinnae provided more accurate results in localization than without pinnae.

Many theories have been advanced on the role of pinnae in localization. For sound sources within the median plane, localization was regarded as influenced primarily by the irregularities of the pinna (Gardner and Gardner, 1973, Searle, 1975) as well as the binaural pinna disparity (Searle, Braida, Cuddy and Davis, 1975). For sound sources outside the median plane, although the modification of a sound by the pinnae was considered as a major factor in localization, different views are held as to the modification process.

Batteau (1967) argued that, since the acoustic information arrives at the ears from the infringing sound front, the perception of the location of a sound source requires a transformation relative to the arriving wave front. He proposed that the external ears perform the requisite transformation by creating a set of delayed replicas of the signal, from the reflections at various points on the pinnae. He developed a mathematical model for the transformation by the pinnae and showed that localization in three-dimension space requires a minimum of four independent paths for the sound to reach the ear drum.

The modification of the original sound by a pinna was seen differently by Blauert (1969), who considered the pinna as a bandpass filter. Depending on the direction of the incoming wavefront, the pinna enhances some portions of the signal frequency spectrum (the preference band); and the relative intensities of these preference bands indicate the location of the sound source.

Although the above findings indicate that the pinna play an important role in sound localization, it is not yet clear whether the pinna is the most important factor differentiating localization and lateralization. For example, it was not clear from Fisher and Freedman's results whether the subject heard a sound as inside his head (IH) or "out there" (OH) when his pinnae were rendered ineffective.

In the following series of experiments, the effects on IH and OH sensation when the pinnae are rendered ineffective, and the effect on localization when the pinnae are pointed backward, are studied, in an attempt to examine the role of the pinnae in externalizing a sound image.

5.3 AUDITORY LOCALIZATION WITH ARTIFICIAL PINNAE

5.3.1 Introduction

In this experiment, a pair of artificial pinnae (No. 5021, Medical Eng. Ass. Inc., Mass., USA) was used. The experiment was divided into 3 parts. Part 1 of the experiment was used to study the suitability of the artificial pinnae for replacing the subject's real pinnae in localization. Localizations with subject's real pinnae are also included to serve as base line data.

In part 2 of the experiment, auditory localization with the pinnae rendered ineffective was studied. This was similar to Fisher and Freedman's experiment. However, in the present experiment, the subjective intra-cranial and extra-cranial responses, rather than the accuracy in localization, were of prime interest.

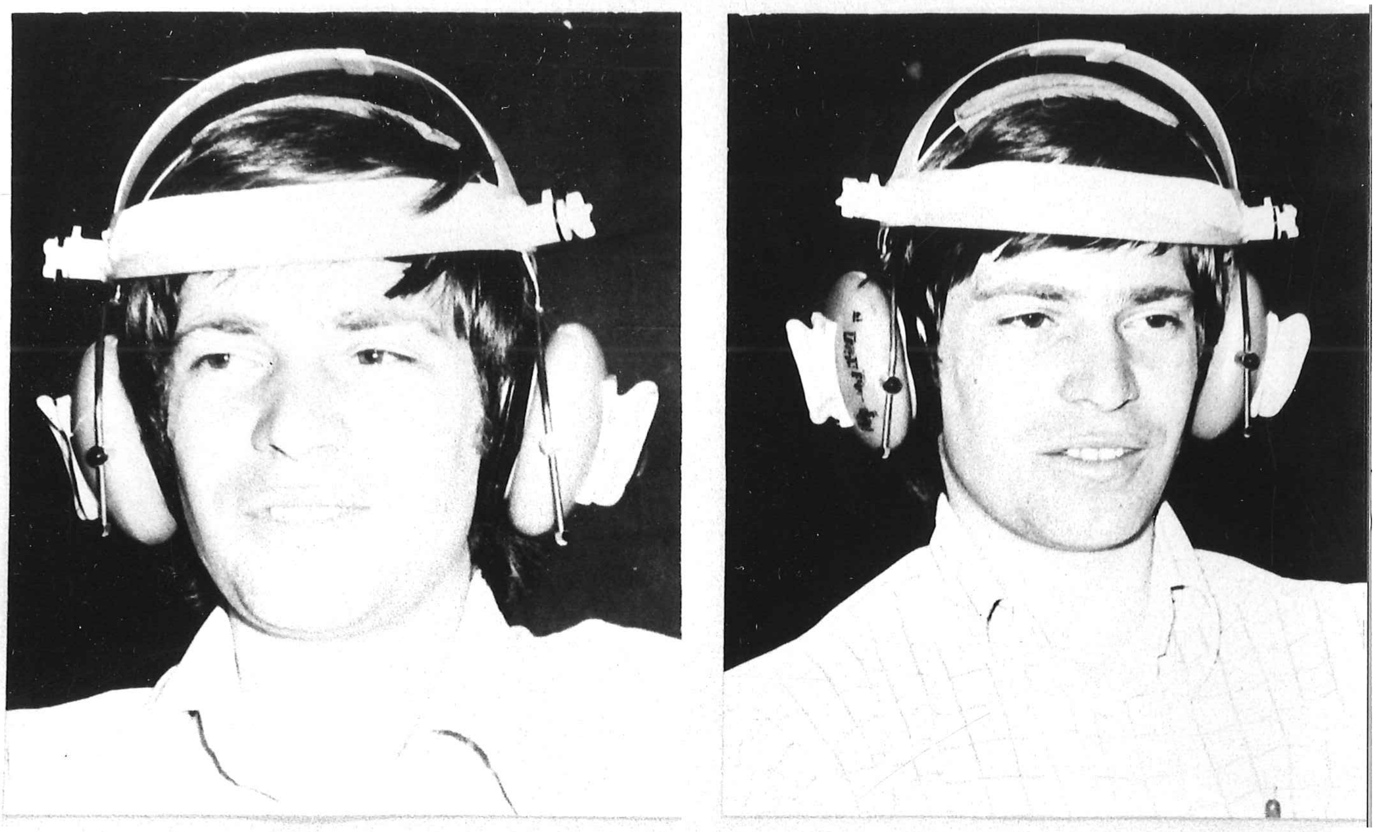
Part 3 of the experiment extended the study to examine the effect on localization when the direction of pointing of the pinnae was reversed.

5.3.2 Apparatus and Procedure

In part 1 and 3 of the experiment, the subject wore the pair of artificial pinnae mounted on a pair of earmuffs (fig. 5.3). The subject listened to sounds through a pair of nylon tubes which ran from the artificial pinnae to his ear canals. In part 2 of the experiment, another pair of earmuffs was used; sounds were presented to the subject through nylon tubes which connected the subject's ear canals to a 5mm hole on each earmuff. The earmuffs provided sound insulation in the order of 40dB.

The blindfolded subject sat in the centre of an anechoic chamber with ambinet noise level measured at 25dB. There were eight identical loudspeakers around him, 2 feet away and at his ear level. The loudspeakers were arranged as: Front, Front-Right, Right, Back-Right, Back, Back-Left, Left, and Front-Left, as shown in fig. 5.4. The subject was asked to report verbally the position of the sound source (presented at random, five times for each position) as one of the eight possible positions indicated above, and whether the sound is heard as "inside" his head or "out there".

A B

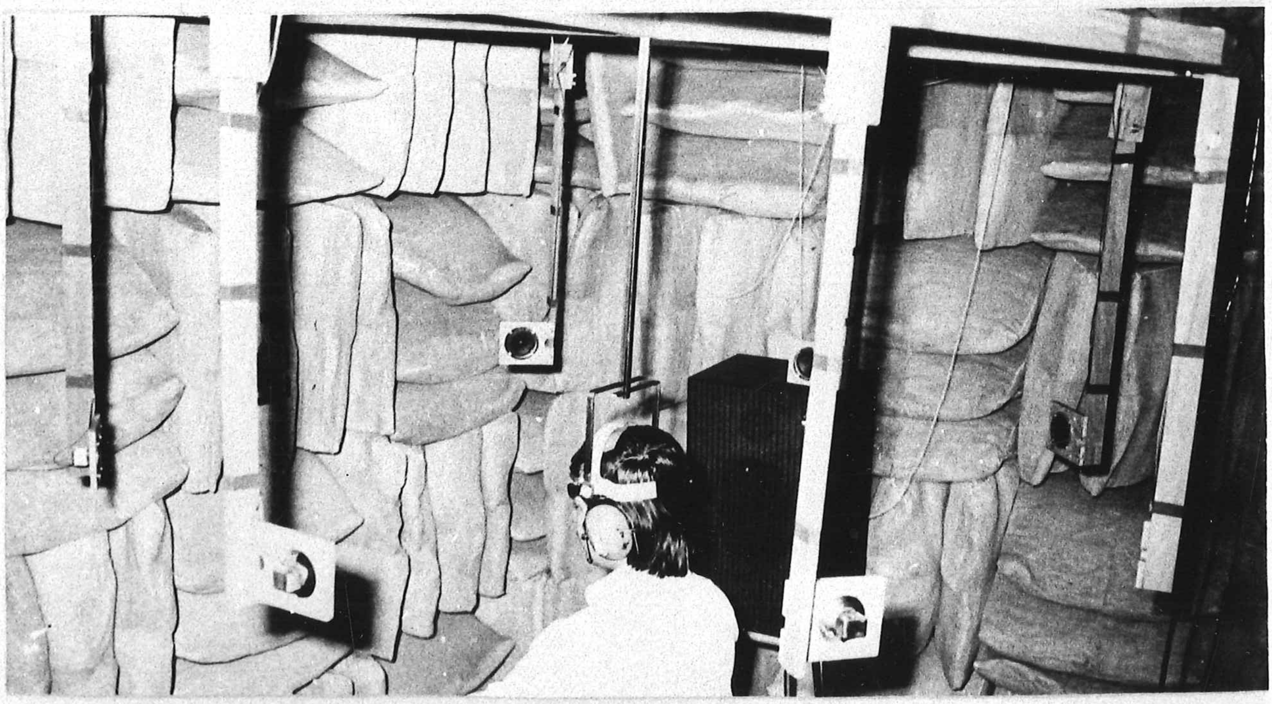


ARTIFICIAL PINNAE MOUNTING

A NORMAL DIRECTION

B REVERSE DIRECTION

FIG 5.3



LOCALIZATION WITH ARTIFICAL PINNAE EXPERIMENT SET UP

FIG5.4

The subject head movement was restricted by means of a plastic head band firmly attached to the centre of the loudspeakers arrangement.

Continuous white noise at 40dB SPL was used as stimulus. A masking sound (white noise, 50dB) was used to obviate any possible cue during the transient period when the sound was turned on.

Five subjects were used in all conditions. None had participated in any psychoacoustical experiment before and none reported any hearing anomalies.

5.3.3 Results

(i) Part 1

The localization with the subject's real pinnae and artificial pinnae (pointed in the normal direction) are shown in fig. 5.5 and 5.6 respectively. To provide a measure of the correlation between the reported response and the true stimulus, a Pearson Produce Moment of Correlation r_{xy} of grouped data (Guilford, 1956) was calculated. This was done by converting the response, x, and the stimulus, y, into numerical data: (F, FR, R, BR, B, BL, L, and FL into 1, 2, 3, 4, 5, 6, 7 and 8).

$$r_{xy} \text{ is given by: } r_{xy} = \frac{\frac{\Sigma x'y'}{N} - M_{x'}M_{y'}}{\sigma_{x'} \cdot \sigma_{y'}}$$

where x', y' = the deviations of the coded value of x and y from their respective means.

M'x and M'y = means of x' and y'

$\sigma x'$ and $\sigma' y$ = deviation of x' and y'

N = total number of trials

For the localization with artificial pinnae, the results were found to correlate +0.96 with the true sound source position. This compared favourably with Fisher and Freedman (1968) results of +0.76 correlation coefficient.

The subjective "in head" and "out there" responses are shown in table 5.1 Even with artificial pinnae, 97.5% of the time, the sound was heard as "out there". The results indicate that the artificial pinnae can be used to replace the listener's own pinnae in auditory localization tasks with a very small error percentage.

Table 5.1:

Subjective impressions of intra-cranial and extra-cranial localization

	Intra-cranial	Extra-cranial	Undecided
Real pinna	0	200	0
Artificial pinna	1	195	3
Artificial pinna rendered ineffective	151	18	31
Artificial pinna in reversed direction	8	189	3

(ii) Part 2

Localization results with the artificial pinnae rendered ineffective are shown in fig. 5.7. It is seen that, under no-pinna condition, sounds from the "front" such as FR and FL positions were heard as coming from BR, BL, or B positions. The results correlated +0.76 with true sound positions. This was comparable with Fisher and Freedman's correlation coefficient of +0.67, and indicated that localization accuracy was substantially degraded when the pinnae were rendered ineffective.

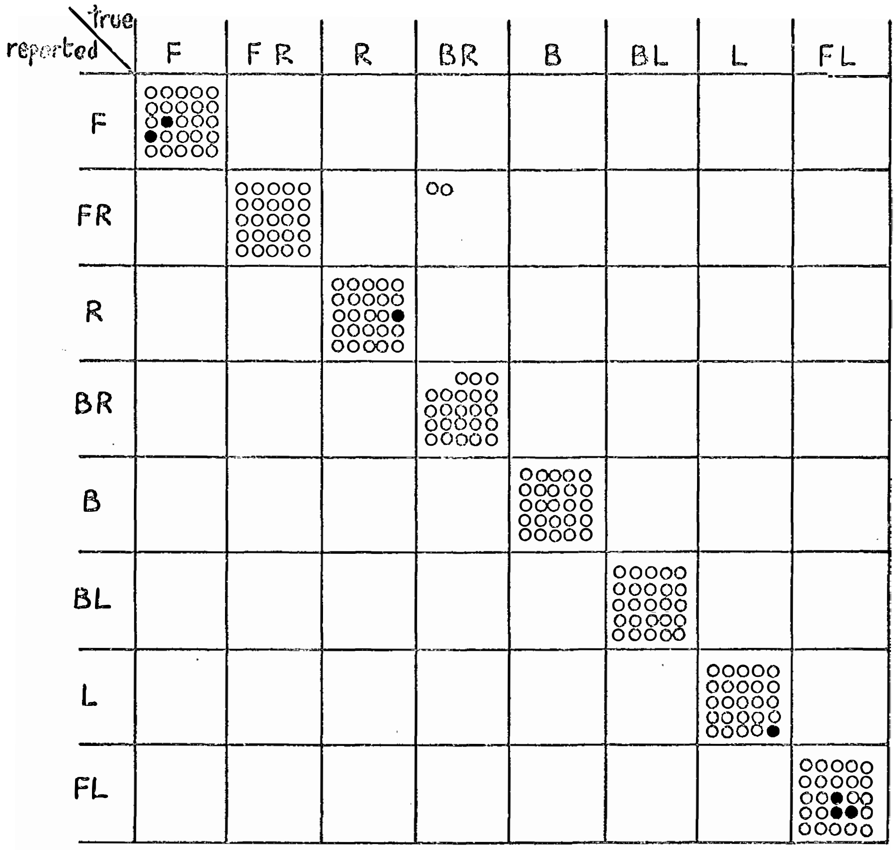
The subjective intra-cranial and extra-cranial responses are also shown in table 5.1. The 75.5% intra-cranial responses indicate a strong correlation between "inside the head" localization and the "pinnae ineffective" condition.

(iii) Part 3

When the artificial pinnae were in the reversed direction, a sound coming from the front position was frequently reported as coming from the back position. Front-back reversions of other sound source positions were also reported. The results are shown in fig. 5.8. Excluding the right and left positions, the results correlated 0.87 with a 100% front-back reversion. Also, most of the time, sounds were heard as outside the head (Table 5.1).

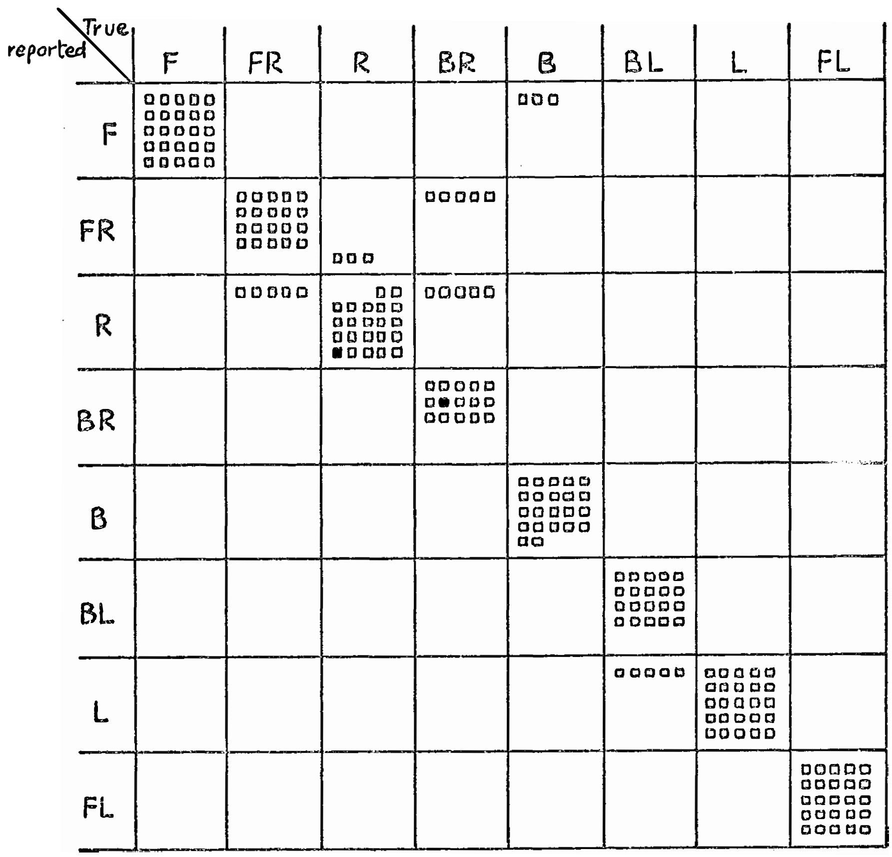
5.3.4 General discussion

When the pinnae were rendered ineffective, sounds were heard as inside the head; and when the pinnae were reversed, sound localization were reversed. These results tend to substantiate the hypothesis that the pinna is the most important factor in sound externalization.



AUDITORY LOCALIZATION WITH SUBJECT'S OWN PINNAE.

FIG. 5.5



AUDITORY LOCALIZATION WITH ARTIFICIAL PINNAE POINTED IN NORMAL DIRECTION

Fig 5.6

reported \ true	F	FR	R	BR	B	BL	L	FL
F	++++				+++			
FR		+++	+	+				
R		+++++ +++++ +++	+++++ +++++ +++++ ++	+++++ +++++ +++++				
BR		+++++ ++	+++++ ++	+++++ +++	++			
B	+++++ +++++ +++++ +++++ +			+	+++++ +++++ +++++ +++++	+		
BL						+++++ +++	++++	+++++ ++
L						+++++ +++++ +++++	+++++ +++++ +++++ +++++	+++++ +++++ +++++ +
FL						+	+	++

AUDITORY LOCALIZATION WITH ARTIFICIAL PINNAE RENDERED INEFFECTIVE.

FIG. 5.7

reported \ true	F	FR	R	BR	B	BL	L	FL
F	ooooo o				ooooo ooooo ooooo ooo			
FR				ooooo ooooo ooooo ooooo oooo				
R		oo ooooo ooooo	ooooo ooooo ooooo ooooo ooooo	o				
BR		ooooo ooooo ooo						
B	ooooo ooooo ooooo oooo				ooooo oo			
BL							o	ooooo ooooo ooooo ooooo
L						ooo	ooooo ooooo ooooo ooooo oooo	
FL						ooooo ooooo ooooo ooooo oo		ooooo

AUDITORY LOCALIZATION WITH ARTIFICAL PINNAE POINTED IN REVERSED DIRECTION.

FIG. 5.8

A pinna may act as a family of reflecting planes, which reflect the incoming signal into the ear canal, thereby producing a set of delayed replicas of the signal. The delays produced by a pinna can vary from 10 μsec to 100 μsec, corresponding to reflecting points from 3mm to 30mm apart. This possibility is strengthened by the results of an experiment conducted by Wright, Hebrank and Wilson (1974) who found that these delays can be easily perceived by the human auditory system. With the delay of 20 μsec, a composite signal (i.e., a signal plus its delayed signal) was found to be recognizable when the amplitude ratio of the signals (delayed over undelayed signal) was 67%. Wright et al. also found that the pinnae reflections caused spectral changes in the auditory signal. This tends to indicate that Blauert's theory of preference band (Blauert, 1969), as , mentioned earlier, is not actually in conflict with the pinna reflection theory originated by Batteau (1967).

5.4 THE PINNA TRANSFER FUNCTION

The localization delays produced by the transformation of a sound front by the pinnae can be obtained by studying the transfer function of a pinna. The delays are of particular interest if the localization mechanism is to be incorporated into the display of a mobility and to produce an "out there" sensation. The transfer function can be obtained by the impulsive method or the cross-correlation method. In the attempt to measure the transfer function described below, the cross-correlation method was employed. The principle and the design of a cross-correlator are described in the following sections.

5.4.1 The cross-correlation function

In a linear time invariant system, the cross-correlation of the input $x_1(t)$ and the output $x_2(t)$ is given by:

$$\Psi_{12}(\zeta) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} x_1(t) x_2(t-\zeta) dt \qquad (1)$$

It has been shown that if the input is white noise, i.e., having constant power density spectrum, (the auto correlation function is a delta-function $\Psi_{11}(\zeta) = \delta(\zeta)$), the cross correlation of the input and output is the impulse response $h(\zeta)$ of the system:

$\Psi_{12}(\zeta)$ can be written as:

$$\Psi_{12}(\zeta) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} x_1(t) dt \int_{-\infty}^{+\infty} h(\Theta) \; x_1(t-\zeta-\theta) d\theta$$

$$= \int_{-\infty}^{+\infty} h(\Theta) d\Theta \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} x_1(t) \; x_1(t-\zeta-\theta) dt$$

Note that $\Psi_{11}(\Theta-\zeta) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} x_1(t) \; x_1(t-\zeta-\theta) dt = \delta(\theta-\zeta)$

Hence: $\Psi_{12}(\zeta) = \int_{-\infty}^{+\infty} h(\Theta) \delta(\Theta-\zeta) d\Theta = h(\zeta) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} x_1(t) x_2(t-\zeta-\Theta) d\Theta$

In this convolution integral, the interval 2T should be sufficiently large c.f. the maximum dealy, ζ_{max}, so that averaging is possible, but it should not be larger than the time in which the individual signal symbols are regarded as correlated so that the signal can still be considered as stationary within the interval of observation. Furthermore, the maximum delay ζmax must be large enough to ensure that at least a full period length of the basic harmonic is included; i.e.,

$$\zeta \max > \frac{1}{f \min}$$

The subdivision of ζ max, i.e. the number of steps $n = \frac{\zeta max}{\Delta\zeta}$ must be large enough so that there are at least 5 - 10 measurement points for the highest harmonic contained in the signal.

5.4.2 <u>A cross-correlator using pseudo-random noise</u>

In cross-correlation technique, the cross-correlator displays the cross-correlation function $\Psi_{12}(\zeta)$ of the tested system as:

$$\Psi_{12}(\zeta) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} x_1(t)\ x_2(t-\zeta)\ dt$$

If the signal is periodic,

$$\Psi_{12}(\zeta) = \int_{-T}^{+T} x_1(t)\ x_2(t-\zeta)\ dt = \int_{-T}^{+T} x_2(t)\ x_1(t-\zeta)\ dt$$

where $x_1(t)$ is the input signal of the system and $x_2(t-\zeta)$ is the output of the system delayed by ζ. This technique involves delaying one signal with respect to another. Conventional methods in acoustical applications using magnetic correlatographs (for example, Hollin, Jones and Fowweather, 1976) or acoustic delay line with hollow tube provided some good results, but they are not convenient to use and require great mechanical accuracy. In the system described below, pseudo-random noise is used as the interrogative signal. The advantage of using pseudo-random noise lies in the fact that the noise, although random, can be exactly duplicated at any time by using a second pseudo-random signal generator (PRSG) having the same initial condition as the first one. Thus the difficulties involved in delaying the output $x_2(t)$, an analogue signal can be simplified by delaying, instead, the starting pulse of the input PRSG.

(i) <u>The cross-correlator block diagram</u>

A typical cross-correlator block diagram is shown in Fig. 5.9. The input system consisted of a PRSG and a transmitting transducer. Call the transmitting (input) signal $x_1(t)$. The signals pass through the system under test and were received by a receiving transducer, the output of which was called $x_2(t)$. $x_2(t)$ went through two paths in the receiving system of the cross-correlator. In path 1, it activated the automatic variable delay network (AVDN) which in turn activated the receiving PRSG. This PRSG produced an exact duplicate of the input signals, but delayed with respect to the receiving signal $x_2(t)$ by a delay time ζ set by the AVDN. This delayed signal was called $x_1(t-\zeta)$. The convolution integral of $x_2(t)$ in path 2 with $x_1(t-\zeta)$ in path 1 gave:

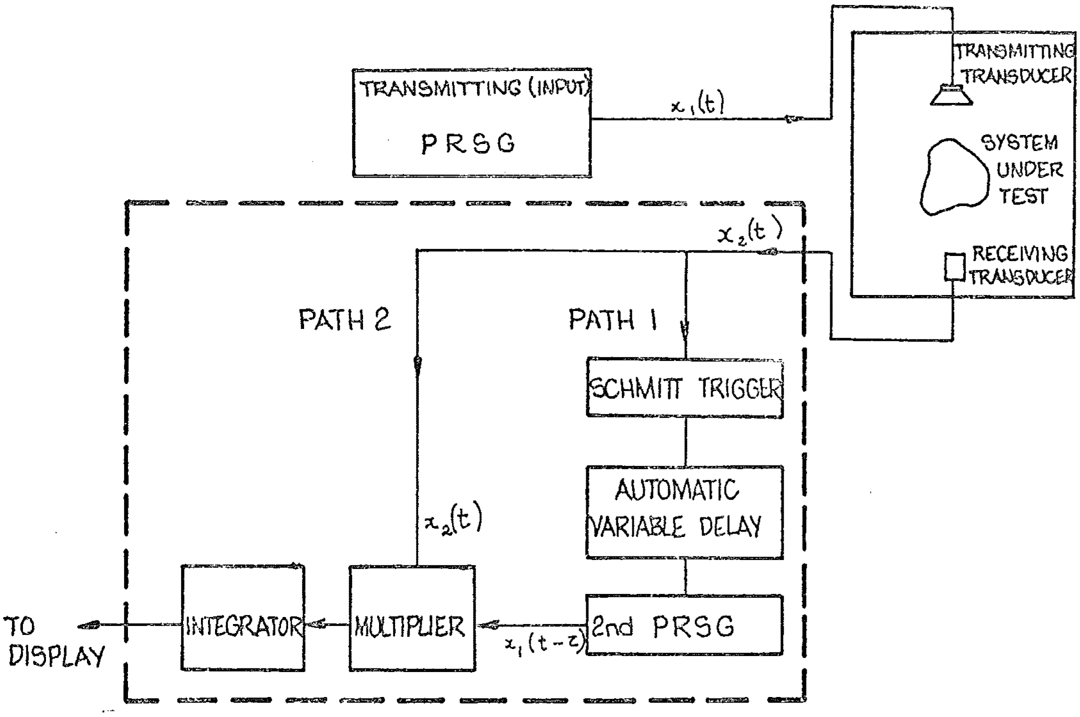
$$\Psi_{12}(\zeta) = \frac{1}{2T} \int_{-T}^{+T} x_2(t)\, x_1(t-\zeta)\,dt$$

In the above cross-correlator, it was assumed that the transmitting and receiving transducers do not have any effect on the impulse response of the system under test. This assumption may not be valid in many cases. Therefore, in the measurement of the impulse response of the pinnae, a duplicate of the transmitting and receiving signal was used as shown in Fig. 5.10. In this system, $x_1(t-\zeta)$ was not the direct output of the receiving PRSG of Fig. 5.9, but the output after modification by transmitting and receiving transducers (Fig. 5.10). By doing so, the effects of transmitting and receiving transducers on the cross-correlation function were eliminated, and the difference between $x_1(t-\zeta)$ and $x_2(t)$ was solely due to the modification by the pinna.

In the next two sections the operation of the PRSG and the AVDN are briefly described. For simplification, the block diagram of Fig. 5.10 is used. The circuit diagrams of the correlator are presented in Appendix 6.

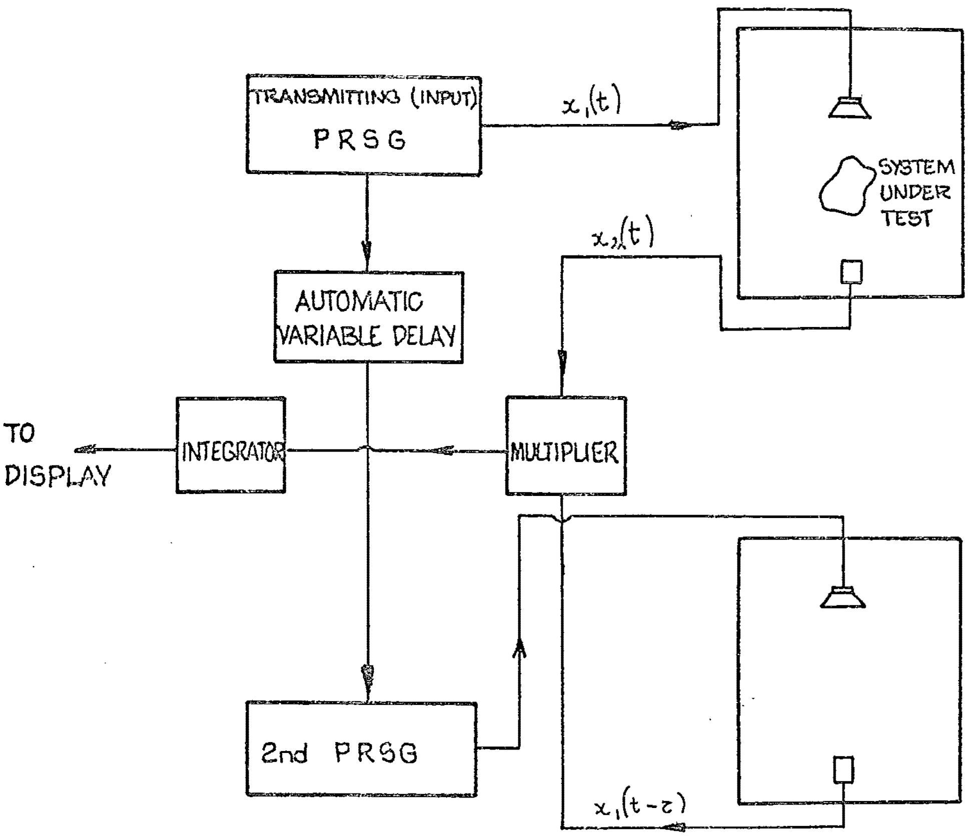
(ii) The pseudo-random signal generator

The pseudo-random signal was generated by summing two different outputs of a shift register through an exclusive-or (Fig. 5.11). If the outputs were the first and the $(2k-1)^{th}$ outputs of the shift register, the shift register produced $2^{2k-1}-1$ pulses of random values of either 1 or 0, then repeated itself. Call $2^{2k-1}-1$ pulses a burst, the PRSG would be made to produce a single burst at a time by stopping the PRSG's clock when the combination of the 2k-1 final pulses of the burst was detected (Fig. 5.11). Two 8-bit shift registers SN 74199 were



THE BLOCK DIAGRAM OF A CROSS CORRELATOR USING PRSG.

FIG. 5.9



THE BLOCK DIAGRAM OF THE CROSS CORRELATOR USED IN THE PINNA TRANSFER FUNCTIONS EXPERIMENT.

FIG. 5.10

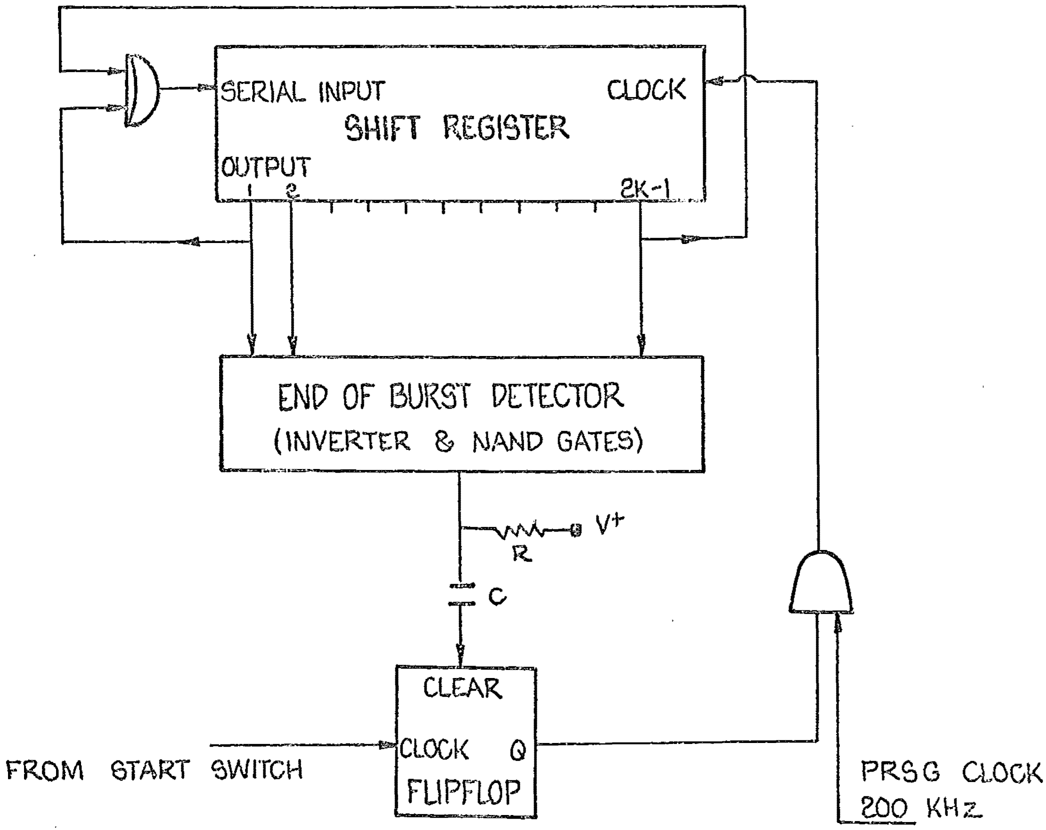
to give $2^k-1 = 15$. The number of pulses per burst was $2^{2^k-1}-1 = 32,767$. The clock rate was 200kHz.

(iii) <u>The automatic variable delay network</u>

The automatic variable delay network, using count-up and count-down counters (CUC and CDC) as shown in Fig.5.12 could be made to produce any number of delay steps by varying the size of the counters. The period ζ of the delay clock determined the time interval between two successive delays. The principle of operation is briefly described here:

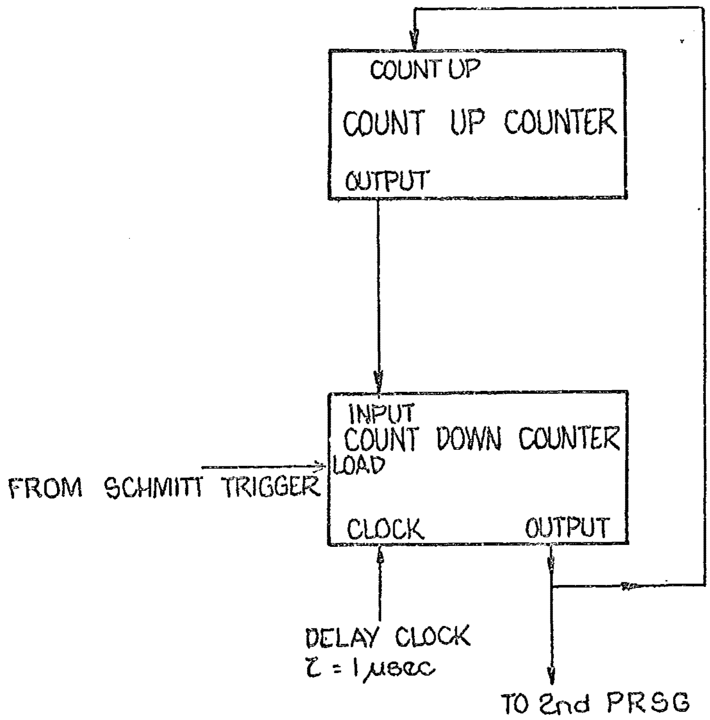
Suppose we have a 1 at the output CUC. When the first burst of transmitting signal is received, a load pulse from the receiving transducer's Schmitt trigger (Fig. 5.9) is applied to the load terminal of the CDC. This load pulse updated the content of CDC to equal to that of the CUC. Upon the application of the delay clock pulse to the clock terminal of the CDC, the CDC will start counting down, 1 per clock pulse, and produces an output pulse when it counts down to 0. The output pulse of the CDC goes to the count-up terminal of the CUC to increase the latter by 1 and, at the same time, starts the second PRSG. The output pulse of the CDC, hence the burst of signal produced by the second PRSG, were delayed by $1 \times \zeta$ sec. with respect to the CDC's load pulse.

When the second burst of transmitting PRSG is received, another load pulse is applied to the load terminal of the CDC and load the value 2 from the CUC into the CDC. It will take $2 \times \zeta$ secs before the CDC produces another output pulse to start the second burst of the receiving PRSG, and so on. The delay of the second PRSG with respect to the transmitting PRSG signal is $n \times \zeta$ sec, where n is the number of burst of signal received.



THE PSEUDO-RANDOM SIGNAL GENERATOR

FIG. 5.11



THE AUTOMATIC VARIABLE DELAY NETWORK

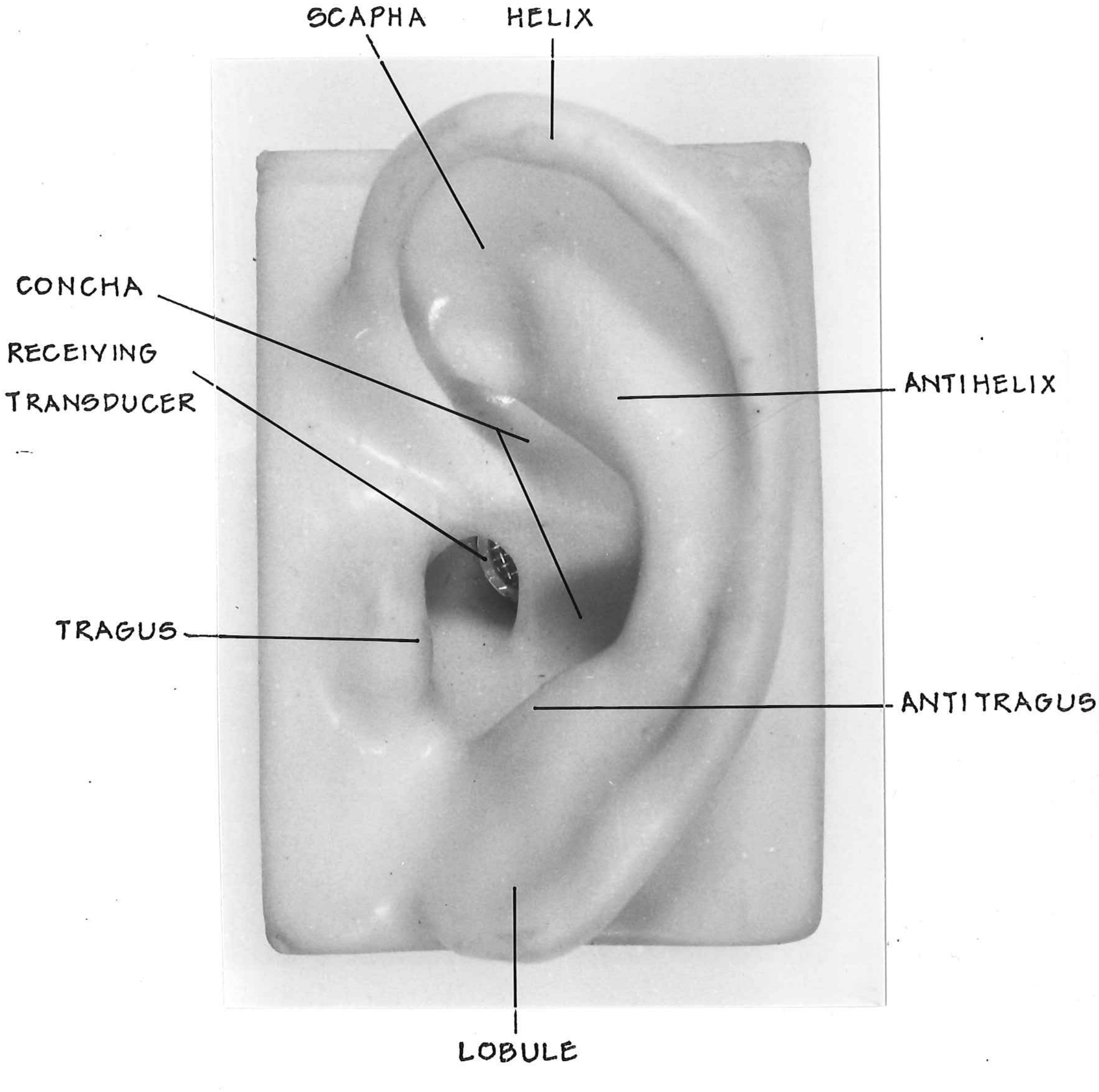
FIG. 5.12

Six 4-bit up/down counter SN 74193 were used in the AVDN to give a maximum of 4086 delay steps of $\zeta = 1$ μsec each.

5.4.3 Experiment set up

Since the resolution of auto-correlation function $\Psi_{11}(\zeta)$ (the impulse response of the testing equipment) is inversely proportional to its bandwidth, to discriminate delays produced by a pinna to within 20 μsec resolution, (20 μsec being the delay perceivable by the human auditory system; Wright et al., 1974) the bandwidth of the testing system must be at least 50 kHz. Therefore wide frequency 75 mm dia. circular ultrasonic transducer with frequency bandwidth of 100 kHz $\pm$ 3dB (Appendix 6) were used as transmitters and receivers, instead of normal audio speakers.

As mentioned earlier, two similar transducer arrangements were necessary to obviate the effect of the transducers and their associated amplifier circuits on the impulse response of the testing equipment. In the 1st arrangement, the receiving transducer was placed inside a dummy head with its diaphragm just behind the entrance to the ear canal (also called the meatus) of an artificial pinna (the external meatus or auricle) (Fig. 5.13). Two rotating shafts were fitted onto the dummy head so that the azimuth and elevation angle of the head could be varied. The angle of rotation was indicated by means of a protractor mounted at the base of the rotating shaft. Fig. 5.14a shows the dummy head mounting for elevation measurement. The transmitting transducer was suspended 1.5m away, directly opposite the artificial pinna. In the 2nd arrangement the transmitting and receiving transducers were suspended 1.5m apart

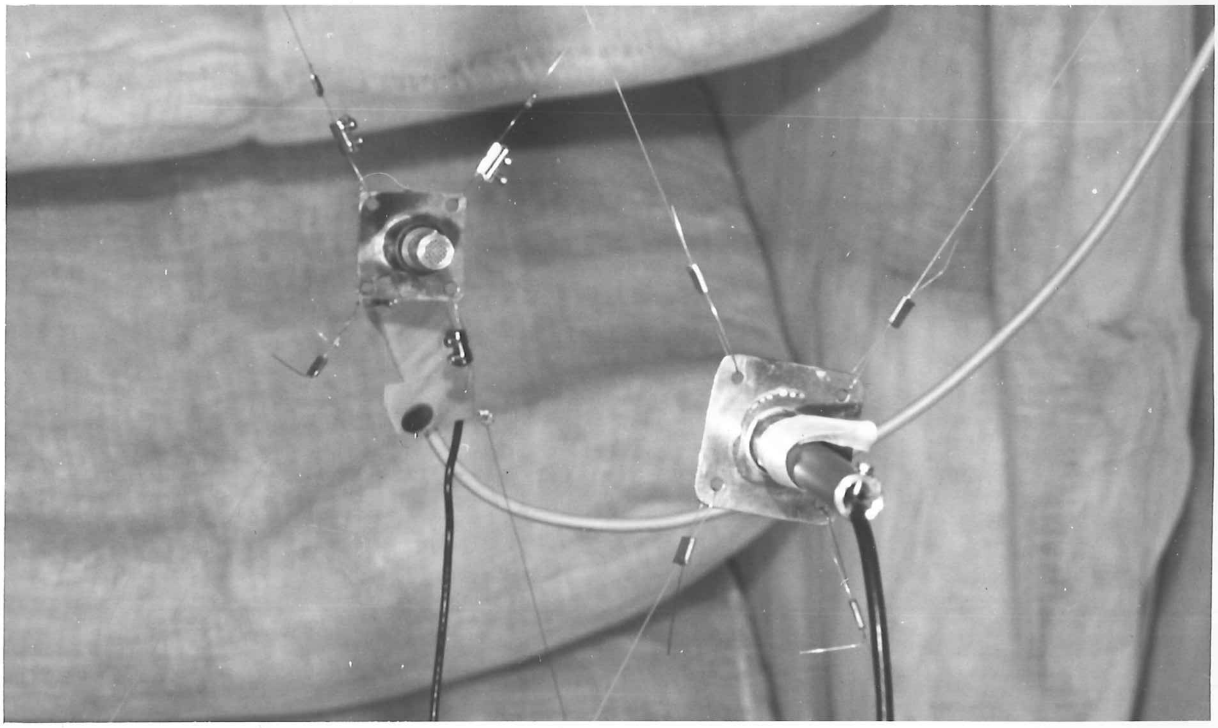


STRUCTURE OF THE PINNA

FIG 5.13

A

B



PINNA TRANSFER FUNCTION EXPERIMENT

(A) 1ST. TRANSDUCER ARRANGEMENT

(B) 2ND. TRANSDUCER ARRANGEMENT

FIG. 5.14

and directly opposite each other (Fig. 5.14.b). The two transducer arrangements were placed in two adjacent anechoic chambers.

Cotton wool was placed in the ear canal to reduce the effect of sound reflecting from the receiving transducer, due to a mismatch in impedance of the receiver diaphragm in replacing the ear drum (Morton and Jones, 1956). (After damping, the pressure transfer function in the ear canal (with the transducer placed at the ear drum position) was found to follow that of the real ear as measured by Wiener and Ross (1946).

Although 4086 delay steps were available, it was soon found that only about 1000 delay steps were necessary to completely plot the transfer function of the pinna. Accordingly, each plot took 200 sec. to complete.

5.4.4 Results and discussion

The impulse response of the testing equipment is shown in Fig. 5.15. Although the response consisted of a main and two side peaks, since the side peaks were sufficiently small (-26dB) the response could be considered as a delta function with a pulse width of about 10 μsec. This corresponds to a spatial resolution of about 3.4mm.

(i) Azimuth Angle

The transfer function of the pinna as a function of the azimuth angle are also shown in Fig. 5.15. There are up to twenty dominant, separated peaks in some of the transfer functions of the pinna. The peak separations varied from 10 μsec to 40 μsec which corresponded to a spatial separation of the reflecting points from 3.4mm to 13.6mm. Due to an initial fixed delay introduced into the transmitting signals in the 2nd transducer arrangement (see timing pulses, Appendix 6), the earlier peaks corresponded to further reflection points. For example, consider the transfer function at azimuth angle $\theta = 60$. The 1st peak, occurring at $\zeta = 440$ μsec, corresponded to the longest delay and therefore was possibly due to the reflection from the upper part of the helix. The last dominant peak, occurring at $\zeta = 575$ μsec corresponded to the shortest path, and hence was most likely due to the direct sound.

In general the peaks in the transfer functions appeared to divide into 4 distinct groups.

The first group, around $\zeta = 450$, was separated from the direct sound by about 160 μsec to 180 μsec. Since this corresponded to a spatial separation of 54mm to 62mm from the ear canal, this group was most likely to be due to reflection from the upper part of the helix and the scapha. The reflection should be negligible for small θ because the scapha tends to block sounds reflected from the helix from reaching the ear canal (Fig. 5.13). The reflection should become more noticeable around 45° to 120° when reflected sounds bounce off the tragus and tunnel into the ear canal. Quantatively, the results in Fig. 5.15 seem to support this observation.

The second group of reflection, occurring around $\zeta = 480$ μsec, was probably due to the reflection from the antihelix. Again due to the structure of the pinna, the reflections were more noticeable for $45^{\circ} < \theta < 120^{\circ}$. This group was separated from the 1st group by 30 μsec, or about 10mm.

VARIATIONS OF THE PINNA. TRANSFER FUNCTIONS WITH AZIMUTH ANGLE.

FIG 5.15

The third group of pulses was separated from the direct pulse by about 60 μsec or 20mm from the ear canal, therefore it was most likely due to reflection from the concha. The presence of this group of pulses in almost all sound source directions was probably due to the parabolic shape of the concha which tended to collect and direct sound toward the ear canal.

The last group was due to the direct sound. It was not noticeable for $\theta < 60^{\circ}$ due to the blocking by the tragus. It became more noticeable around $\theta = 60^{\circ}$, however its amplitude was still small since only a small area of the receiving transducer was exposed to the direct sound. Its amplitude became more dominant around $80^{\circ} < \theta < 90^{\circ}$ where the exposed area of the receiver reached a maximum. The group became insignificant for $\theta > 100^{\circ}$.

(ii) Elevation

The transfer function at 90° azimuth angle were plotted for elevation angles (ε) of 0° to 150°. They are shown in Fig. 5.16. Again the pulses seemed to form into 4 distinct groups. (It is noted that due to a slight change in the position of the dummy head when the axis of rotation was changed, the pinna transfer function at 90° azimuth angle in Fig. 5.15 is slightly different from that at 90° elevation (Fig. 5.16), however the main feature (i.e. 4 groups of reflection) was still clearly shown).

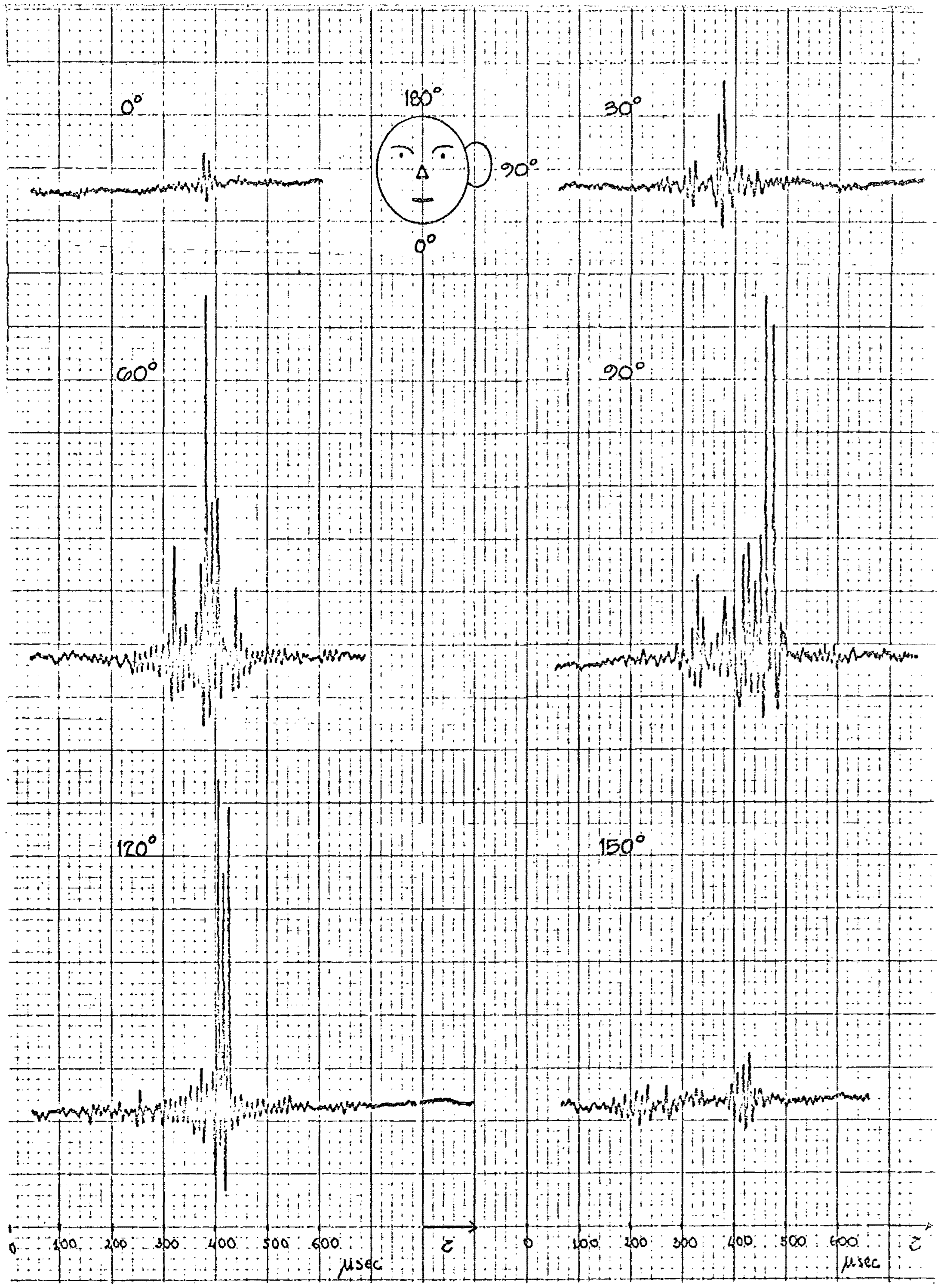
The first group of pulses was observable at 30° elevation (ζ=320μsec). The group became more noticeable at 60° and 90° and then became negligible for elevation angles greater than 120°.

The pulses were 150 μsec from the direct pulse, or 51mm from the ear canal, therefore they are most probably due to the reflections from the upper part of the helix.

The second group of pulses (ζ=380) was the most dominant group at elevation angles from 0^{o} to 60^{o} and became less significant as the elevation angle increased above 90^{o}. This group came from reflectors 30 - 40mm from the meatus and therefore is most likely caused by the reflections from the antihelix. Observation of the geometry of the pinna revealed that the reflection from the antihelix would follow the same pattern as the 2nd group of pulses, and hence tend to confirm the stated origin of these pulses.

The third group of pulses (ζ=400-420) was insignificant for ε up to 30^{o}. Its amplitude reached a maximum around elevation angles between 90^{o} and 120^{o} and decreased again for elevation angles greater than 150^{o}. This group was separated from the direct sound by about 40 μsec, and therefore was due to reflectors 13mm from the ear canal. It was most probably caused by reflections from the concha.

The fourth group of pulses was observable at ζ = 460-480 for elevation angles around 60^{o} to 90^{o} and non-existant for other elevation angles. They are most likely due to the direct sound. Again observation of the geometry of the pinna tends to confirm this. (At small elevation angles ($\varepsilon < 60^{o}$) the direct sound was blocked by the lobule and the antitragus; at large elevation angles ($\varepsilon > 90^{o}$) the direct sound was blocked by the helix and the scapha).



VARIATIONS OF THE PINNA. TRANSFER FUNCTION
WITH ELEVATION.

FIG. 5.10

(iii) General

Many attempts have been made to determine the transfer function of the pinna (Rudlin, 1972; Blauert, Laws and Platte, 1974; Meller, Siebrasse and Mehrgardt, 1974; Odsmundsen and Gjaevenes, 1974; Price 1974), and to produce a replica of the external ear (Bauer, Rosenheck and Abbagnaro, 1967; Teraniski and Shaw, 1968; Gardner and Hawley, 1973). In the following sections, these transfer functions are briefly described and compared with those obtained in this experiment. The existing external ear replicas are also studied and the effects of the obtained transfer function on the reproduction of the external ear are examined.

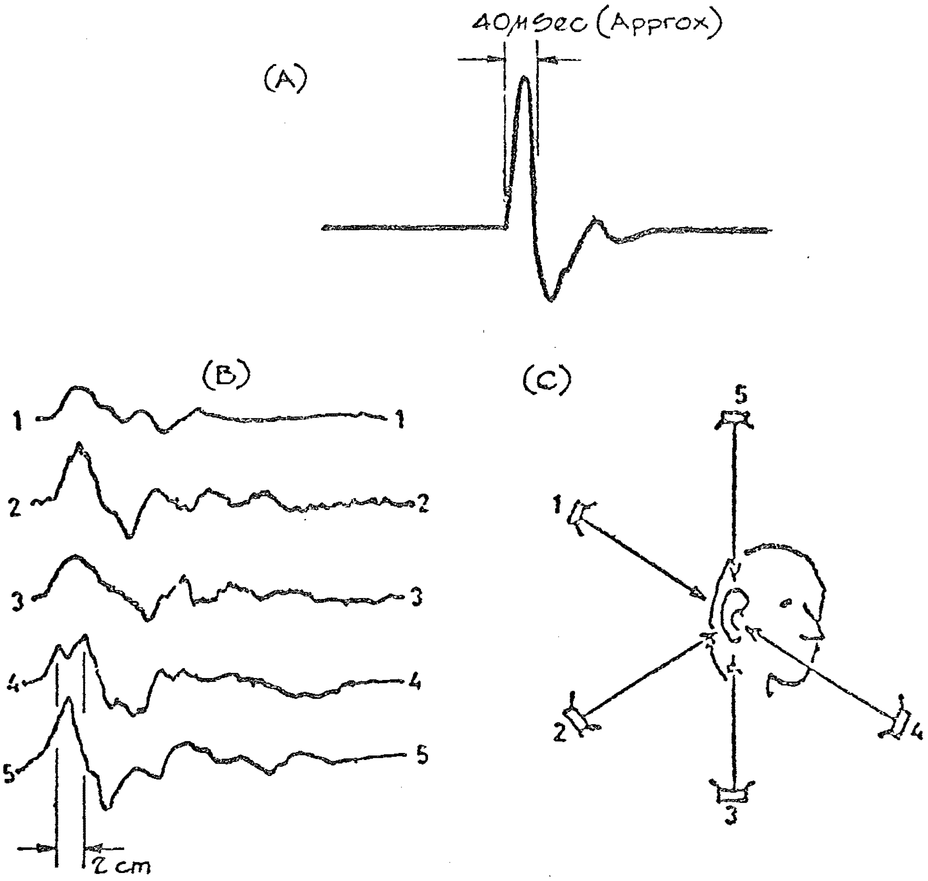
By recording the reflections from a pinna due to a 40 μsec impulse, Rudlin found that the impulse response of the pinna consisted of the direct pulse and a series of positive and negative pulses (Fig. 5.17). Since the path differences from the latter pulses to the direct pulse varies from 20 to 160mm, much larger than the dimension of the pinna, Rudlin speculated that the pulses were probably due to reflections to and fro across the concha or from the meatus.

In studying the harmful effect of impulse sound on human auditory system, Price also produced the impulse response of the pinna. From a gun fire impulse of a US Army M.16 rifle, the impulse response of a model ear (designed by Teraniski and Shaw, 1968) showed multiple peaks of decreasing amplitude at about 200 μsec interval (Fig. 5.18). Because only the transfer function at $\Theta = 90^{o}$ was provided, the cause of these multiple peaks are not clear. However since the separation of these peaks correspond to a spatial separation of more than 60mm, a little bigger than the physical dimension of an actual ear, it is unlikely that these peaks were due to reflectors on the pinna, but they were rather due to a ringing effect in the model ear.

The impulse response measured by Blauert et al. showed 4 dominant peaks at 200 μsec interval (Fig. 5.19). However since the impulse used was not very sharp, the positions of the reflectors corresponding to these peaks were not certain.

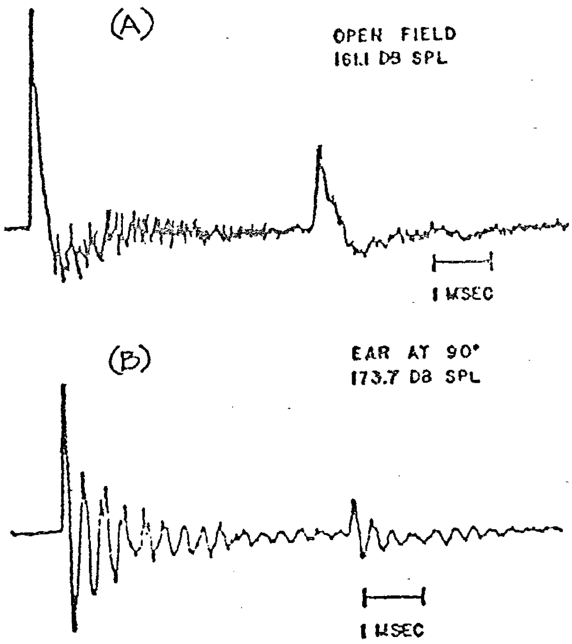
Most puzzling are the impulse responses measured by Odsmunsden and Gjaevenes, who used a shot gun to provide an impulse of 10 μsec rise time and 200 μsec decaying time (Fig. 5.20). With the microphone at the ear drum position, again the ringing effect as in Price's results were observed. However, when the microphone was placed at the entrance to a block ear canal, the results resembled those obtained by Blauert et al. Since the peaks were separated from the direct sound by 150 μsec to 600 μsec (Fig. 5.20, c, $0 = 0^{o}$) these peaks are likely to come from reflectors outside the actual pinna (50-200mm from the ear canal).

In general, the impulse responses previously available did not clearly show the modification of sound by the pinna. The 1st reflected pulses of these transfer functions was separated from the direct pulse by 60 μsec (Rudlin) to 150 μsec. (Odsmunsen and Gjaevenes) and therefore was likely to be due to reflection from the pinna. However subsequent pulses were too separated from the direct pulse to be reflection from the actual pinna. Many of the responses also showed a series of gradually decaying and regularly separated peaks. These peaks do not seem to demonstrate the transfer function of the pinna,



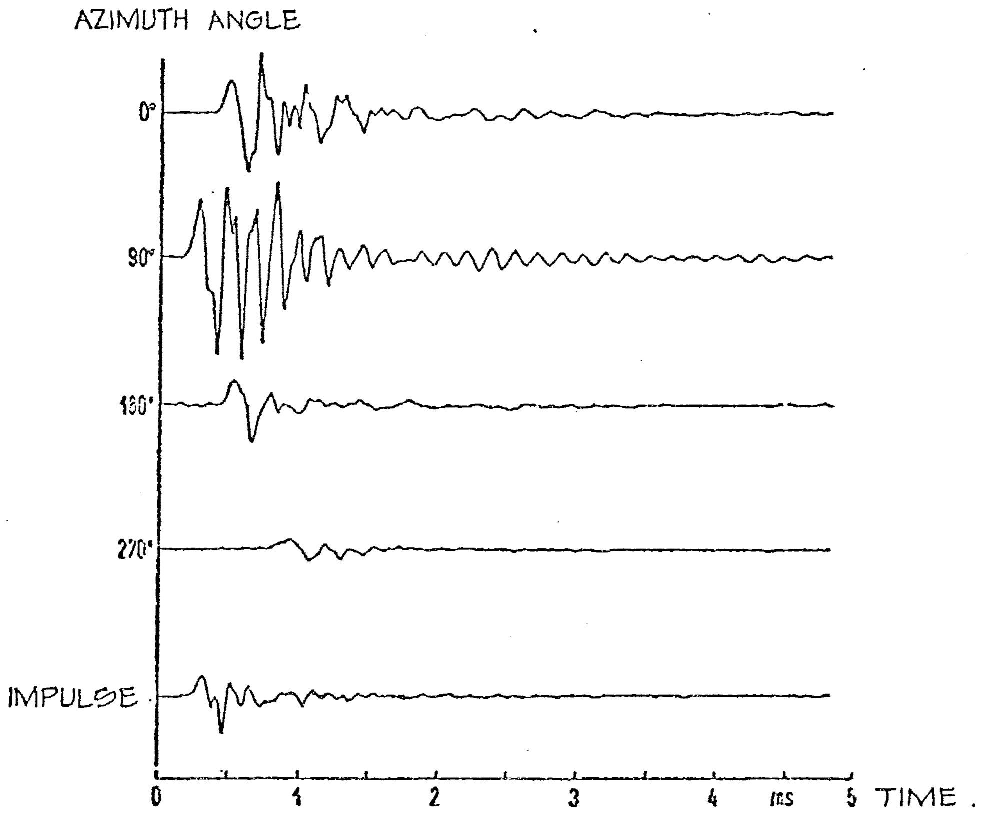
PINNA TRANSFER FUNCTION (RUDLIN 1972)
(A) IMPULSE
(B) TRANSFER FUNCTIONS.
(C) POSITIONS OF SPEAKERS (MEATUS BLOCKED), MICROPHONE AT MEATUS ENTRANCE.

FIG 5.17



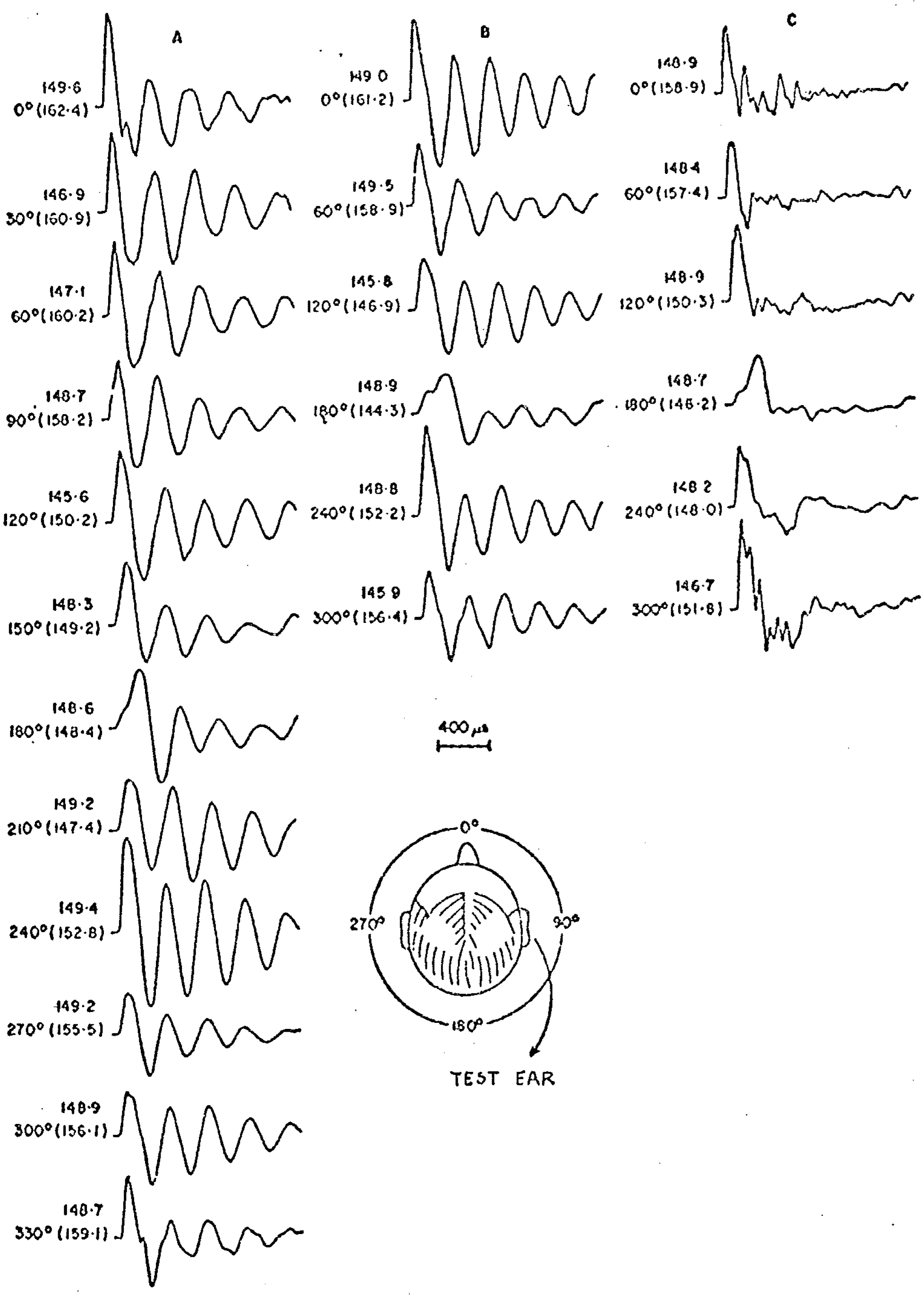
PINNA TRANSFER FUNCTION (PRICE, 1974)
(A) IMPULSE
(B) TRANSFER FUNCTION.

FIG 5.18



PINNA TRANSFER FUNCTION (BLAUERT ET AL 1974)

FIG 5.17



IMPULSE RESPONSE OF THE ARTIFICIAL EAR (OSMUNDSON & GJAEVENES 1974)

COLUMN A: MICROPHONE AT THE EARDRUM POSITION ARTIFICIAL HEAD WITH PINNA.

COLUMN B: ARTIFICIAL HEAD WITHOUT PINNA.

COLUMN C: MICROPHONE AT ENTRANCE TO BLOCKED EAR CANAL, ARTIFICIAL HEAD WITH PINNA.

THE NUMBERS SHOWN ARE FREE FIELD SOUND PRESSURE LEVEL, ASIMUTH ANGLE AND (IN BRACKETS) THE PEAK SPL OF THE MODIFIED SIGNAL.

FIG 5.20

but rather a ringing effect in the ear canal.

The transfer functions obtained in this experiment seem to supply a more detailed spatial resolution of the pinna than previsouly available. Spatial resolution was provided at 3.4mm. Three main groups of reflectors (the upper part of the helix, the antihelix and the concha) were identified and their effects on the transfer function, as the direction to a sound source was varied, could be clearly monitored. The reflectors caused the original sound to be duplicated at delay intervals ranging from 20 μsec to 60 μsec.

The existence of four groups of sound reaching the ear canal (three delayed and one direct) tends to substantiate Batteau's analysis of the pinnae that, for localization in a 3-dimension space, a sound should reach the ear canal by a minimum of 4 independent paths.

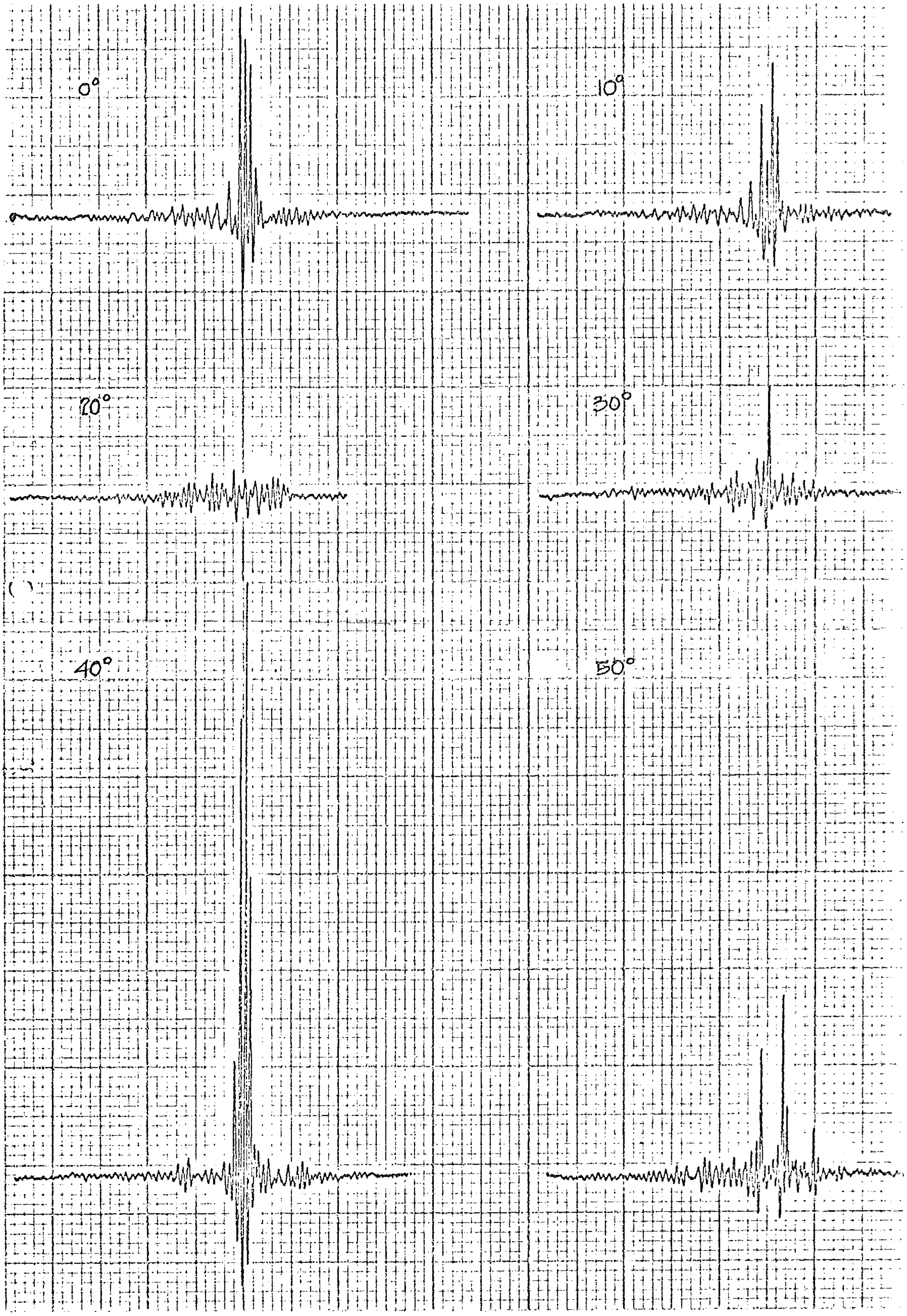
The magnitude of the delays has been found to be within the detection capability of the human auditory system (Wright et al 1974). This again tends to substantiate the hypothesis that the pinna is the most important factor in auditory localization.

Many attemps have been made to produce a replica of the human external ear, however none has been successful in reproducing the kind of change in the transfer function with direction and elevation as shown in Fig. 5.15 and 5.16. The aim of many existing replicas was to provide a means of testing acoustical equipments (such as headphones), therefore most of the external ear reproduction was concerned only with the pressure transfer function of the ear canal but not that of the external meatus itself. (Bauer, Rosenheck and Abbagnaro, 1967 ; Gardner and Harley 1973).

The model ear produced by Teranishi and Shaw (1968) presents a step forward in external ear reporduction, where the effect of the pinna was represented by a simple geometry of a rectangular flange and an inclined shallow cylindrical cavity. While this model showed a pressure transfer function of the ear canal similar to that of a real ear (as measured by Wiener and Ross, 1946), a comparison of the pinna transfer function as measured by Price (1974) (Fig. 5.18) and that obtained in this experiment (Fig. 5-15) tends to suggest that the model ear has been oversimplified to accurately represent an actual pinna.

The evidences gathered so far tend to suggest that an external ear replica should produce, at the entrance to the ear canal, a set of at least 3 delayed replicas of the original sound. However, while the mechanism of the auditory localization was somewhat revealed, reproducing the effect of the pinna by an electrical network does not seem to be an easy task, because the variation of the transfer function with elevation and azimuth angle does not seem to follow any easily defined fashion. The variation can be clearly seen by observing, say, the transfer functions of the pinna at 10^{o} increment in azimuth angle, from 0^{o} to 50^{o} (Fig. 5.21).

The drastic change of the reflecting pulses with direction (and elevation) of a sound source tends to confirm Rudlin's opinion (Rudlin, 1972) that the transfer function can not be easily realized using straight forward electronic techniques



VARIATIONS OF THE PINNA. TRANSFER FUNCTION
WITH 10° INCREMENTS IN AZIMUTH ANGLE.

FIG. 5.21

suitable for use in a portable mobility aid.

5.5 LOCOMOTOR PERFORMANCE UNDER FREE FIELD AND DICHOTIC LISTENING CONDITION

It has been argued, in Chapter two, that in a mobility aid, if the sound image of an object can be projected into space, the localization of the object may be more natural. The object then can be easier to locate and this may lead to better control of locomotion. This hypothesis has not been tested yet because suitable means to measure mobility performance were not available. However, with the completion of a computer-linked locomotion monitoring system at this University by Brabyn and his co-workers (Strelow, Brabyn and Clark, 1976), locomotor performance of a subject in a large sound-treated laboratory (17m x 11m) could, for the first time, be measured objectively and accurately. It was then possible to compare locomotion control performance of subjects under free field and headphones listening conditions and to determine whether the change in the listening conditions could produce any significant change in locomotor performance. This was done in a series of experiments described below.

The experiment was divided into two parts. Part 1 studied locomotion of "unpracticed" subjects who have not performed any auditory control task under dichotic presentation before and were given very little training. Part 2 of the experiment studied in more detail the effects on locomotion of a "practiced" subject when several conditions of dichotic and free field presentation were employed.

5.5.1 Part 1: "unpracticed" subject

(i) Procedure and apparatus

In this experiment, walking in a straight line toward an object, was chosen as the locomotor control task. The subject was asked to walk in a straight line from a starting point 'A' to the object situated at 'B', 10m from 'A'. Since the distance involved was twice the range of the actual Single Object Sensor, a computer was used, instead of the actual device, to produce the spatial information. (Apart from the maximum range, other characteristics of the simulated auditory stimulus were the same as those of the SOS).

The blindfolded subject wore a headband connecting to a measuring system so that the relative position (distance and direction) of the subject and the object can be accurately monitored. The relative position was then sampled at the rate of five samples per second and processed by the computer to produce the appropriate auditory signal.

Under dichotic listening condition, an interaural amplitude difference (IAD) was used to provide the necessary lateralization cues. The auditory stimulus was presented to the subjects through a pair of headphones firmly attached to the headband. Two values of IAD were tested; 0.5dB/degree (the average IAD used in the Binaural Sensory Aid), and 1dB/degree. They were denoted HP.5 and HP 1 respectively.

Under free field listening conditon, denoted FF, the auditory stimulus (both the right and the left channels) was, instead, emitted from a single loudspeaker attached to the object, approximately 1.5m above ground level.

At the beginning of each trial, the subject was guided to the starting point "A". He was asked to turn round until a sound was heard equally loud in both ears (i.e., he was facing toward the direction of the object) and then walk, in a straight line, toward the object. He was told to stop when he was about 0.5m from the object. The amount of turning at the beginning of each trial was randomised and ranged from 45° to 300°. No visual feedback was given during the experiment.

Five subjects were used in the experiment. Each was given two practice trials for each listening condition; the results were computed from the next six trials. The order of the conditions was randomised between subjects. For each subject, the experiment lasted about 15 minutes. The subjects have not participated in any mobility experiment before. None reported any hearing anomalies.

(ii) Measurements

In the straight line walking experiment, the two measurements considered as most relevant are: The RMS deviation from ideal path and the RMS deviation from a straight line. The methods of measurement are briefly described below:

The ideal path was considered as a straight line connecting the starting point "A" and the object position "B". The co-ordinates of "A" and "B" were fixed during the whole experiment. The RMS value of the perpendicular distances from the subject's trajectory (at sampled points) to the ideal path is called RMS deviation from ideal path (RMSDIP).

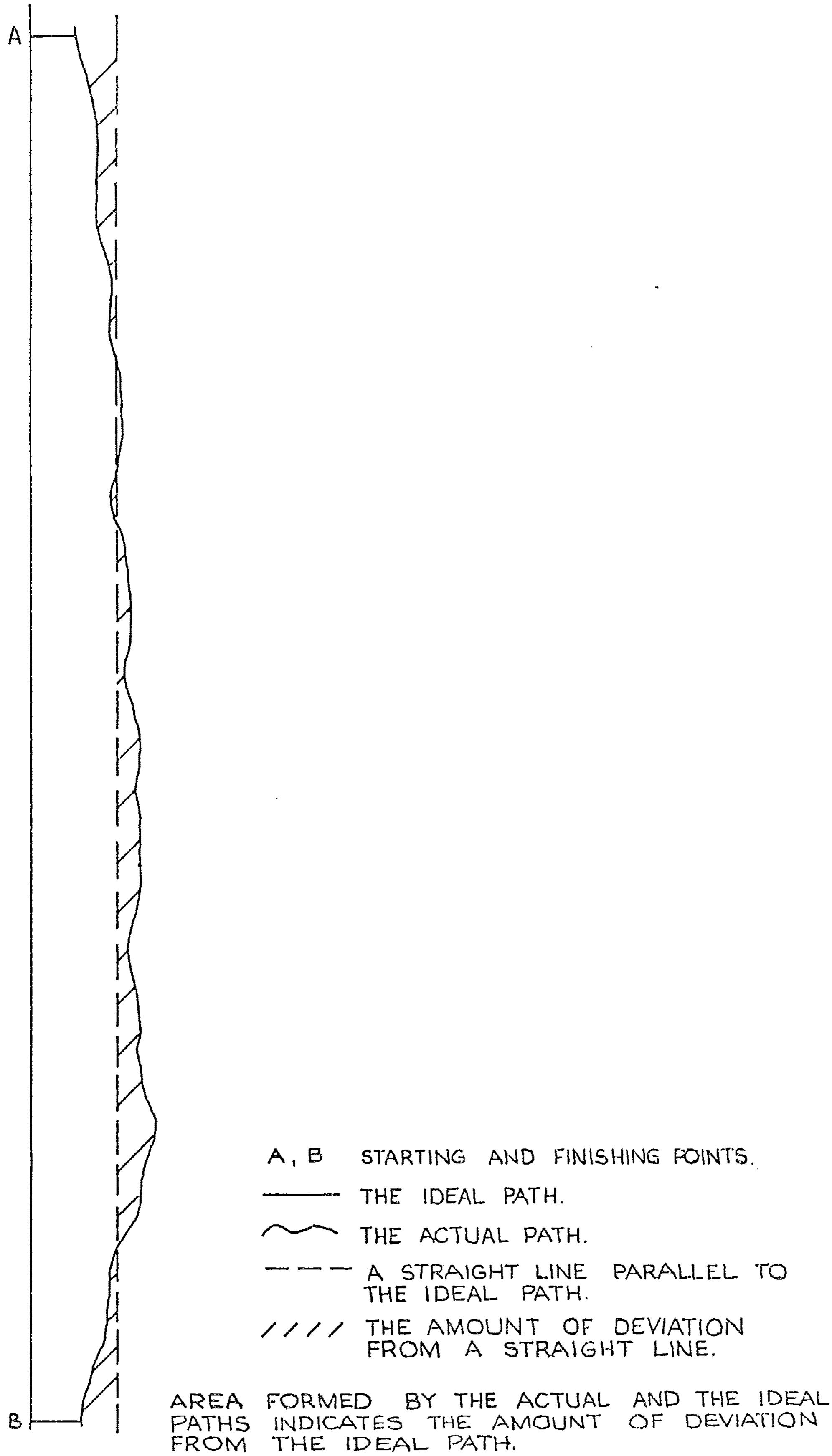
Since the subject had to turn round a certain angle to be in the direction of the object before each trial, it was not always possible to position the subject at the exact starting point "A". To be less restrictive about the starting and finishing positions, deviation from a straight line (RMSDSL) rather than the ideal path was used: A straight line was formed parallel to the ideal path. It was separated from the latter by the average value of the perpendicular distances of the subject's trajectory from the ideal path. The RMSDSL is a measurement of the deviation from this straight line.

In summary, RMSDSL indicates how straight the subject's path was and RMSDIP indicates how far from the ideal path the subject's path was. Fig. 5.22 shows a hypothetical travel path and demonstrates the difference between RMSDIP and RMSDSL.

(iii) Results and discussion

The mean and standard deviations of RMSDIP and RMSDSL of five subjects are presented in table 5.2. The values of RMSDSL indicates that subjects tended to walk straighter under free field than under dichotic listening condition. Test of significance between the means indicated a significant difference between the HP. 5 and the free field conditions at the 0.05 level ($t = 4.84$, $df = 4$). The RMSDIP indicated that the subject's path was a little closer to the ideal path under free field condition than under dichotic listening condition. However, statistic test shows no significant difference between the two conditons at the 0.05 level ($t = 1.73$, $df = 4$).

When the magnitude of the lateralization cue was increased, locomotor control performance improved. There was



MEASUREMENTS OF MOBILITY PERFORMANCE IN A HYPOTHETICAL STRAIGHT LINE WALKING TASK.

FIG. 5.22

no statistical significance between the HP1 and the free field conditons. Also, it was found that performances under dichotic conditions improved with practice at a much faster rate than under free field condition. Typical learning curves are shown in Fig. 5.23.

The use of a novel and artificial display seemed to produce an initial performance inferior to that under a more natural display of free field listening condition. However the improvement in performance with increasing lateralization constant and with practice tends to suggest that the magnitude of the lateralization cue and a small amount of practice may have a more profound effect on the control of locomotion than any subjective differences between headphones and free field listening conditions. The second part of the experiment was designed to test this hypothesis.

5.2.2 Part 2: Practiced subject

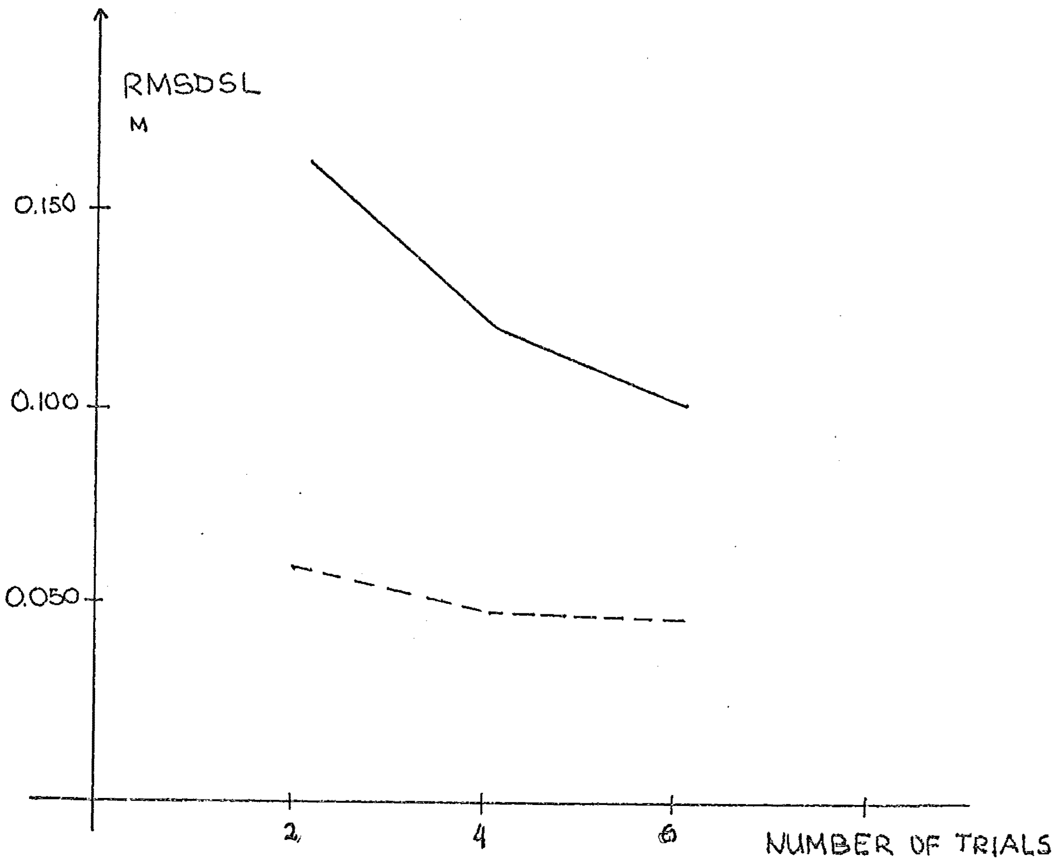
(i) Procedure

In this experiment, apart from the three listening conditions employed in the previous experiment (HP.5, HP 1, and FF), two more conditions were added. They were free field listening condition with constant continuous 30Hz square waves presented via the loudspeaker (CFF) and headphones listening condition with IAD being 2dB/degree (HP2). In each of the five conditions, the subject was given 20 trials; the results were computed from the last 10 trials. The conditions were tested in separate sessions, 2 or 3 days apart. Each session lasted about 20 minutes. The tested sequence was HP2, CFF, HP.5, FF, and HP1.

Table 5.2: Approaching an object. Performance under dichotic and free field listening conditions. Unpracticed subjects.

		HP.5	HP 1	FF
RMSDSL (m)	Mean	0.112*	0.081	0.069*
	SD	0.025	0.024	0.017
RMSDIP (m)	Mean	0.238	0.208	0.167
	SD	0.061	0.067	0.074

* Indicates significant difference (P < .05, "t" test)



THE EFFECT OF LEARNING ON MOBILITY PERFORMANCE
MEAN RMSDSL OF 2 TRIAL BLOCKS OF A TYPICAL "UNPRACTICED" SUBJECT (HP 5)

FIG. 5.23

The same approaching a target task was used. Other procedures and the apparatus were also the same as in the previous experiment.

From the five subjects participating in the previous experiment, a subject with average RMSDSL and RMSDIP was chosen for this experiment.

(ii) Results and discussion

The results are tabulated in table 5.3. Under dichotic presentation, the results indicated that mobility performance improved with increasing lateralization cue. Performance was also found to improve noticeably with practice, especially in the first 10 trials. A typical learning curve is shown in Fig. 5.24.

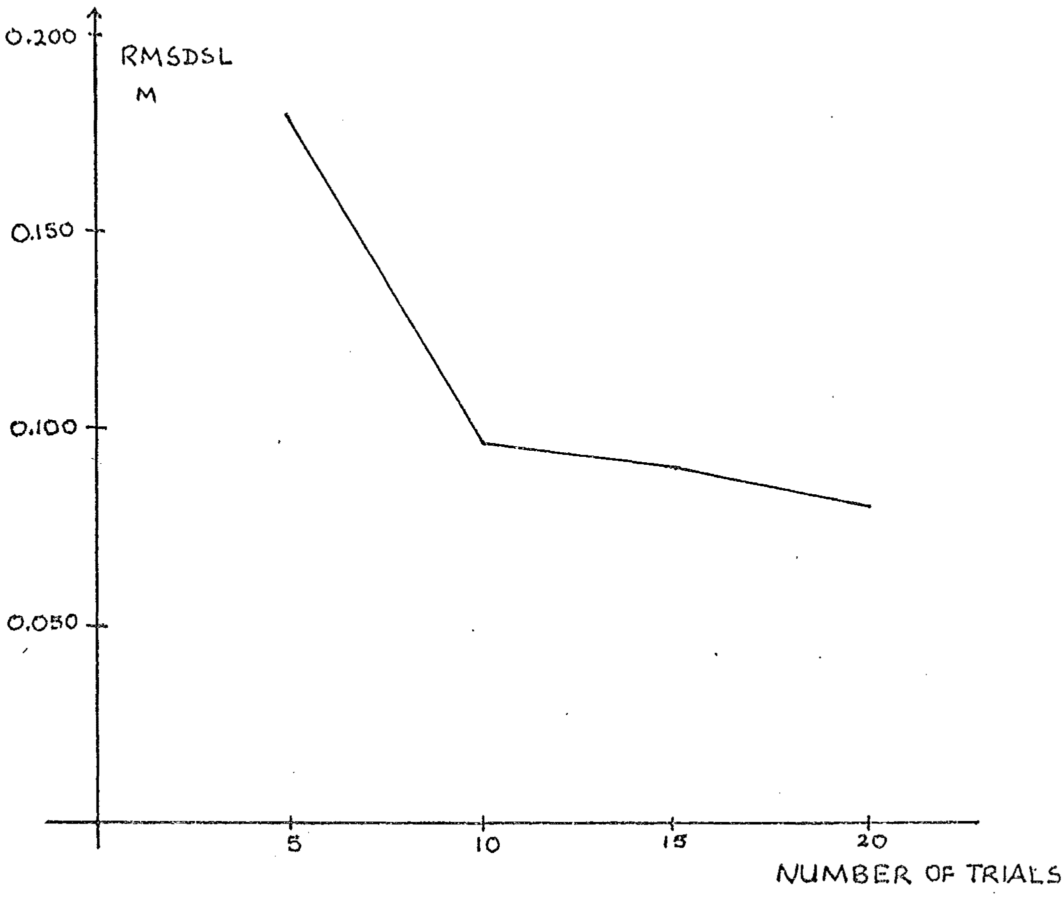
Under free field listening condition, control of locomotion was better with the auditory stimulus of the simulated SOS than with a constant and continuous sound (the latter was deprived of the loudness shaping, due to the lack of directivity of the simulated beamwidth, and the distance-pitch cue).

In comparing the two listening conditions, it is seen that although the performance under FF condition was better than the dichotic presentation with normal IAD (HP.5), the difference was not statistically significant ($t = 2.1$, $df = 9$ and $t = 1.78$, $df = 9$ for RMSDSL and RMSDIP measurements respectively). When the lateralization cue was sufficiently magnified (2dB/degree), control of locomotion under dichotic presentation became the same or marginally superior to that under free field condition.

Table 5.3: Approaching an object. Performance under dichotic and free field listening conditions. Practiced subject.

		FF	CFF	HP.5	HP1	HP2
RMSDSL (m)	Mean	0.065	0.086	0.095*	0.075	0.060*
	SD	0.022	0.044	0.037	0.025	0.025
RMSDIP (m)	Mean	0.155	0.161	0.194*	0.219	0.108*
	SD	0.053	0.104	0.072	0.113	0.084

* Indicates significant difference (P<.05, "t" test)



TYPICAL EFFECT OF LEARNING ON MOBILITY PERFORMANCE OF A "PRACTICED" SUBJECT. MEAN RMSDSL OF 5 TRIAL BLOCKS. (HP. 5)

FIG. 5.24

5.5.3 Conclusion

It has been shown that the differences in performances between dichotic and free field listening condition was reduced to a statistically insignificant level by a little more practice (from six trial to 20 trials). Since statistical test showed no significant difference in the control of locomotion between the dichotic and the free field listening conditions for a subject with a little more practice, it cannot be said that the change from localization to lateralization was exerting a differential effect on the locomotor control performance of the subject. Furthermore, since the increase in the lateralization constant elevated the dichotic performance to about the same level as the free field performance, it can be concluded that the magnitude of the lateralization cue can exert a more important effect on the control of locomotion than the subjective differences between lateralization and localization.

In view of the above conclusion and in view of the enormous amount of difficulties in electronically externalizing a sound source, it was decided that a lateralization, instead of localization, mechanism is to be used in the Single Object Sensor. The study in the remaining of this thesis is restricted to normal IAD (0.5dB/degree) only.

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CHAPTER 6

LABORATORY STUDIES ON SPATIAL PERCEPTION AND LOCOMOTOR CONTROL WITH THE SINGLE OBJECT SENSOR

6.1 INTRODUCTION

With the choice of the lateralization mechanism resolved, this chapter concentrates on the spatial perception and locomotion control using the information provided by the auditory stimulus of the Single Object Sensor, with particular reference to laboratory settings.

Spatial perception can be separated into perception of direction and distance to objects. In the SOS, the direction is determined by the interaural amplitude difference (IAD), while the distance by the rate of repetition of the audio pulses.

The coding of the direction to an object by IAD in the SOS is similar to that in the Binaural Sensory Aid. Since it has been well documented elsewhere (Rowell, 1970; DO, 1977; Brabyn, 1977), it will not be studied any further here. The coding of distance, on the other hand, is quite different from that of the BSA; therefore distance perception in the SOS is studied in details in the first part of this chapter: First of all, it is shown that the auditory stimulus of the SOS can be considered as a train of periodic pulses (Section 6.2). The equal interval change in pitch of the periodic pulses is then experimentally studied (Section 6.3) to provide an indication of the perceived change in the distance to an object.

Apart from the pitch coding, loudness is another cue that can be used in auditory distance estimation. The equal loudness contours of the periodic pulses are studied in Section 6.4 to investigate the requirements in combining loudness and pitch in the coding of the distance to an object.

The control of locomotion in a laboratory with the SOS is examined in Section 6.5. A number of control tasks, ranging from a simple task of walking parallel with a row of poles to a more complicated task of circumnavigating unknown shapes, were used. Using a computer-linked monitoring system, it was possible to measure, accurately and objectively, several aspects of the locomotion of a subject. The measurements included average speed, deviation from a straight line, deviation from an ideal path, as well as plots of the subject's trajectories. From these measurements, it was then possible to objectively compare the usefulness of the SOS, with other types of sensory inputs, such as vision, spatial memory and Binaural Sensory Aid, in the control of locomotion in laboratory settings.

6.2 THE AUDITORY STIMULUS

In a laboratory setting, the commonly-used objects are poles of various sizes and heights. The sound f (t) representing a pole is shown in Fig. 6.1a. Under static condition, it has a similar form to a train of periodic pulses, filtered by a R - C low pass filter, with cut off frequency at about 5kHz (Fig. 6.1b). The frequency spectrum F_n of the audio pulse train f (t) is shown in Fig. 6.2 using Kay Elemetrics Co.'s sonagram and can be approximated by a Fourier series:

$$F_n = \frac{2\pi A\zeta}{T} \sum_{-\infty}^{+\infty} \mathrm{Sinc}\left(\frac{n\pi\zeta}{T}\right) \delta(\omega - n\omega_o) \quad \text{for } o < f < 5\text{kHz}$$

where A = amplitude of the audio pulse train

ζ = pulse width

T = pulse period = $\frac{2\pi}{\omega_o}$

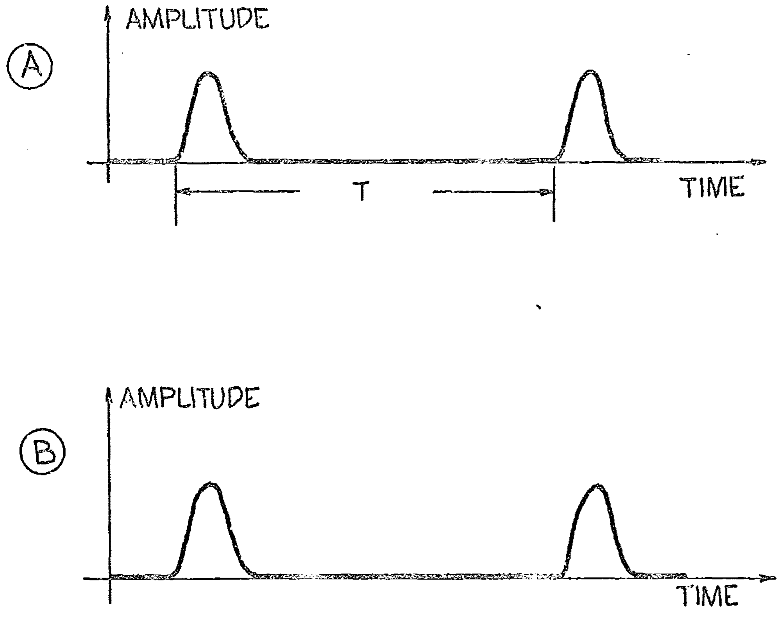
Under dynamic conditions, as in the case of approaching an object, a small movement of the user's head can be induced. This results in changes in the transmitting and receiving angles of the ultrasonic signal. Since the transmitting and receiving transducers are directional, a fluctuation in the echo amplitudes is observed. The fluctuation (Fig. 6.3), is small, in the order of 1.5dB, and is not normally noticed by the user.

More noticeable is the change in pitch of the auditory stimulus due to changes in the distance to the object. In general, the pitch is found to increase with decreasing distance. However, the exact relation between pitch and the distance to an object is not yet well established. Since the distance is inversely proportional to the rates of repetition of the auditory stimulus, the perception of change in pitch as a function of the rates of repetition is studied in the next section to determine the above relation.

6.3 PERCEPTION OF RELATIVE CHANGES IN THE DISTANCE TO AN OBJECT

With the distance to an object being determined by the pitch of the auditory stimulus, the perception of the relative changes in the distance depends on the perceived changes in pitch.

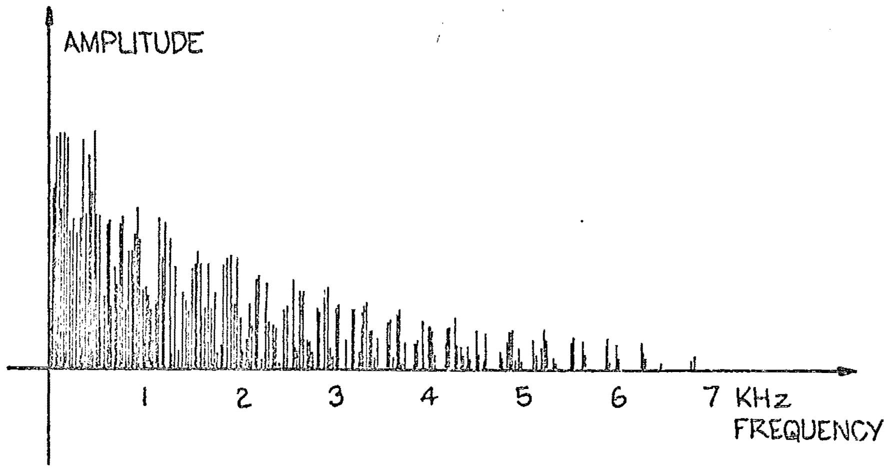
For tones, the changes in pitch are well established and can



Ⓐ THE AUDIO PULSE TRAIN F(t) AS RECTIFIED FROM THE ECHOES OF A LAMP POST.

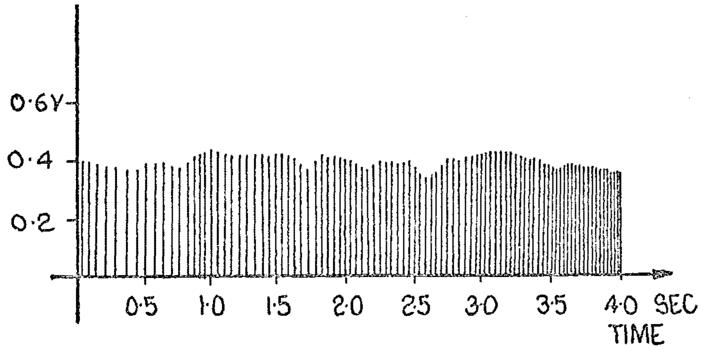
Ⓑ A TRAIN OF PERIODIC PULSES FILTERED BY A RC LOW PASS FILTER. (Fo = 5 KHz)

FIG 6.1



THE FREQUENCY SPECTRUM OF THE AUDIO PULSE TRAIN F(t) IN FIG. 6.1

FIG 6.2



ENVELOPE OF THE ECHO AMPLITUDES PRODUCED BY THE SINGLE OBJECT SENSOR FROM A WOODEN POLE WHEN A USER APPROACHES IT AT A SPEED OF 1m/sec.

FIG.6.3

be determined by various scales, notably the Just Intonation, the Equal Temperament, and the Pythagoren Tuning (Ward, 1970). However, there is no commonly accepted scale for pitch of a complex sound such as the periodic pulses. The pitch depends not only of the fundamental frequencies of a sound (Schouten, 1938), but also on the characteristics of the sound waveform envelope (Mathes and Miller, 1947; Licklider, 1955).

The following experiment was designed to establish the changes, in equal intervals, of the pitch of the periodic pulses so as to determine the perceived changes in the distance to an object.

6.3.1 Prodedure

A pitch matching technique was used to determine the equal change in pitch of periodic pulses.

The whole range of possible rates of repetition (40 to 1280 pps) of the audio pulses was divided into five sections such that their fundamental frequencies formed a five-octave range: 40 - 80, 80 - 160, 160 - 320, 320 - 640, 640 - 1280Hz. A pair of periodic pulses with the rates of repetition being 190.24 and 269.28 pps was used as a pair of reference sounds. They were chosen so that their fundamental frequencies corresponded to the third and the ninth semit (Equal Temperament scale) of the third octave.

The subject, seated in an anechoic chamber with the ambient sound level measured at 25dBa, was presented with this pair of reference sounds as a pair of test sounds with rates of repetition being FR_1 and FR_2. He was asked to vary FR_2 by means of a 10-turn potentiometer so that the pitch interval of the test sounds was the same as that of the reference pair.

At the beginning of each trial, the pair of reference sounds (each lasting for 1 second, and with 1 second silence interval between them) was presented. Then, after 1 second silence interval, the pair of test sounds was presented. Again, each test sound lasted 1 second. There was also a 1 second silence interval between the test sounds. After that, the test sounds were automatically repeated until the end of each trial. During each trial, the subject could listen to the reference sounds again, simply by pressing the "reference" switch provided. When the subject was satisfied that the two pitch intervals were the same, he signalled the experimenter, seated in an adjacent room, by means of a control switch.

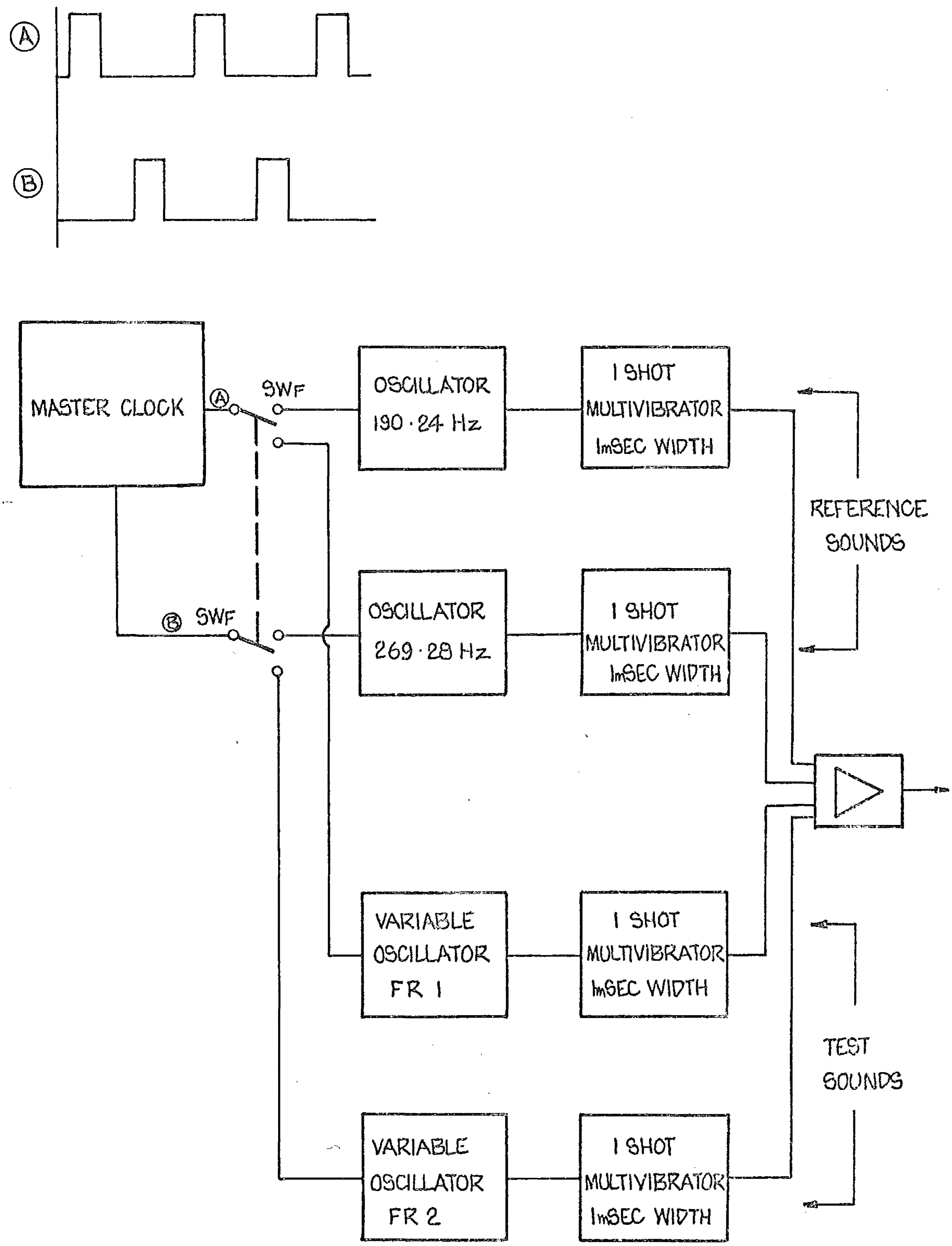
Nine values of FR_1 were chosen. Their fundamental frequencies corresponded to the first and the ninth semit of the first four octaves and the first semit of the last octave. Each was tested six times.

6.3.2 Apparatus

The diagram of the switching apparatus is shown in Fig. 6.4. The pulse trains were presented to the subjects through a pair of KOSS PRO A4 headphones. The rates of repetition FR_1 and FR_2 were measured by a frequency counter (Advance TC11).

6.3.3 Subjects

In the pre-experimental trials, it was found that subjects with experience in the musical field performed the task much more easily and more quickly than subjects with no background in music. Consequently, eight "naive" subjects and two trained musicians were used in the experiment. None reported any hearing



SWF : 'REFERENCE' SWITCH

BLOCK DIAGRAM OF THE SWITCHING APPARATUS IN THE PITCH OF PERIODIC PULSES EXPERIMENT.

FIG. 6.4

anomalies.

6.3.4 Results and discussion

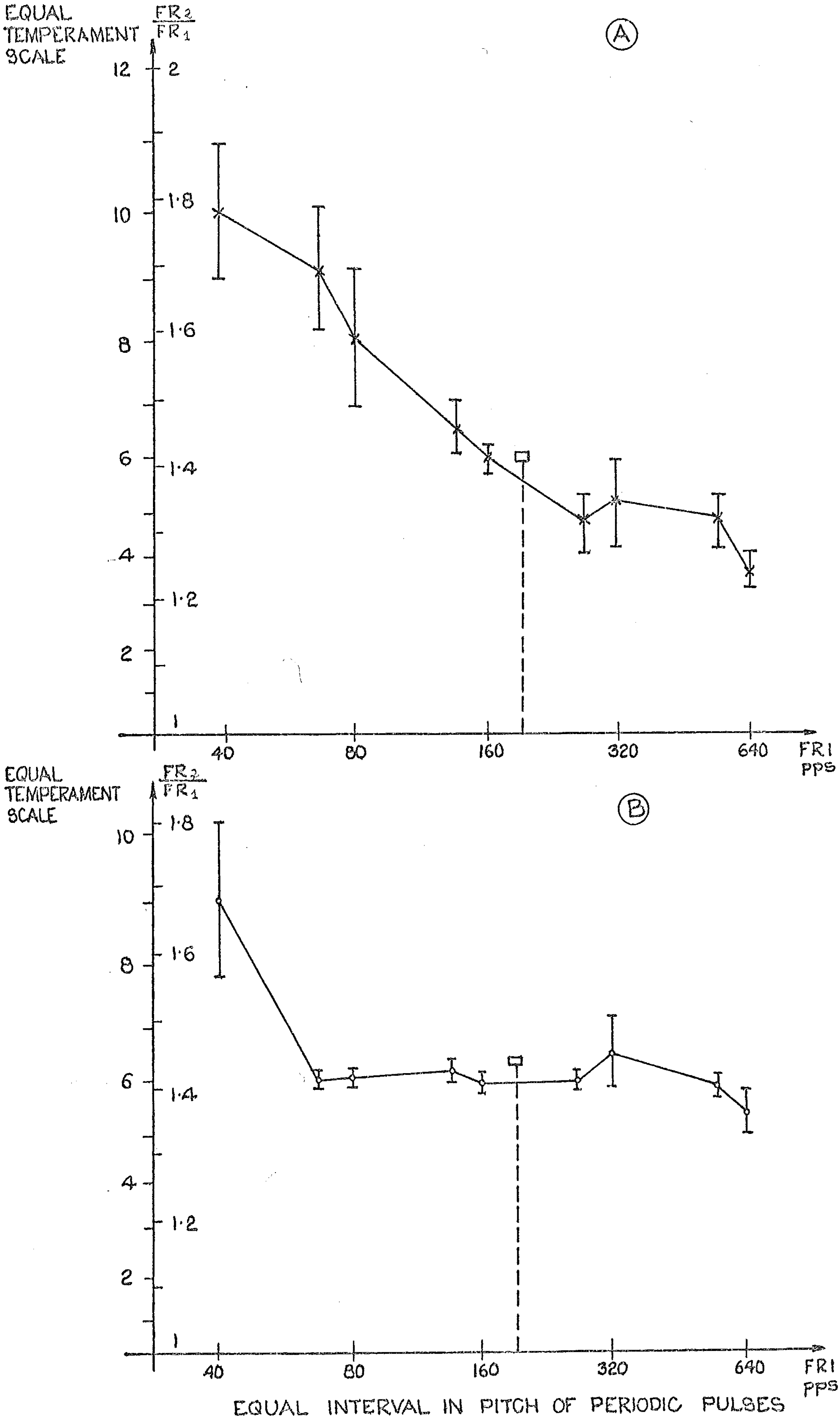
Subjects were able to perform the task with ease, although some difficulties were reported in the matching at very low rates of repetition. In general, the pitch is reported to increase with increasing rates of repetition.

The mean and standard deviation of the results are shown in the form of FR_2/FR_1 in Fig. 6.5a and Fig. 6.5b for naive subjects and trained musicians respectively. The equal temperament scale with 12 equal intervals in pitch (semit) is also shown as a reference. The dotted line represents the reference rates of repetition.

For naive subjects, a considerable fluctuation in the FR_2/FR_1 ratios was observed, especially at low rates of repetition. Furthermore, the ratios seemed to depend on FR_1, being smaller at higher FR_1.

For trained musicians, except at very low FR_1, the fluctuation in the FR_2/FR_1 ratios was much less than that of naive subjects. The results obtained from trained musicians indicated that equal interval changes in pitch of periodic pulses result in a constant ratio of the rates of repetition.

This, together with the report of increasing pitch with the rates of repetition, implies that the pitch of periodic pulses is proportional to its rate of repetition. This finding tends to confirm the results obtained by Flanagan and Guttman (1960) who found that the pitch of periodic pulses was determined by the number of pulses per second at low rates of repetition and by the fundamental frequency (a linear function of the number of pulses per second) at higher rates of repetition.



▭ : PITCH INTERVAL OF THE REFERENCE SOUNDS

(A) : NAIVE SUBJECTS

(B) : TRAINED MUSICIANS

FIG. 6.5

The apparent dependance of the FR_2/FR_1 ratios on FR_1 observed in the results from "naive" subjects (Fig. 6.5a) could be attributed to the subjects' lack of experience in pitch determination. The rather large ratio of FR_2/FR_1 observed at very low FR_1 in the results obtained from trained musicians could be due to the ineffectiveness of the headphone at low frequencies (headphones frequency response: 60 - 15000Hz $\pm$ 3dB).

In terms of distance perception, conclusions on two important areas can be drawn:

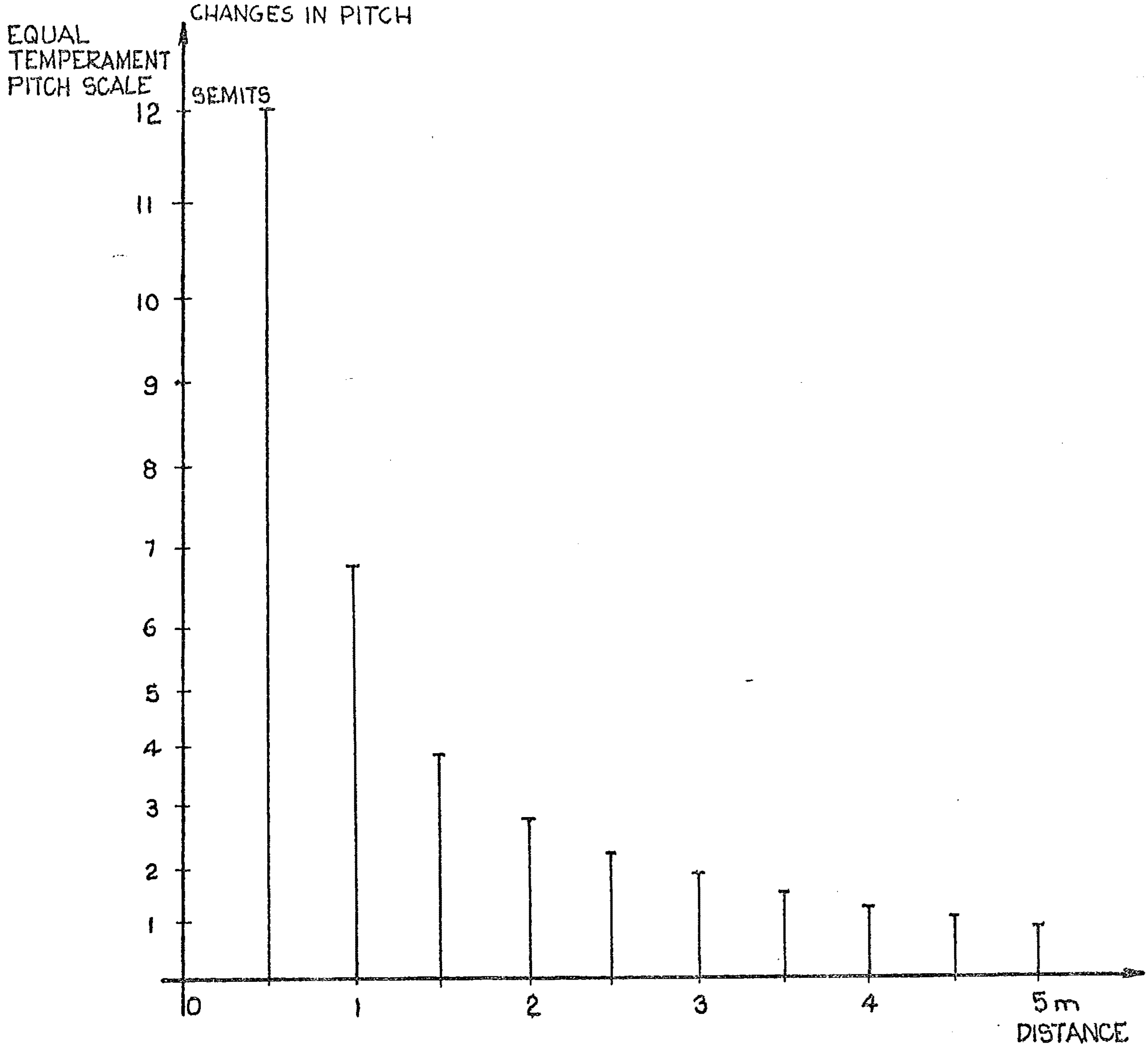
(i) <u>Perceived changes in the distance to an object due to changes in pitch</u>:

Since the distance is inversely proportional to the rate of repetition of the audio pulses, it is inversely proportional to pitch of the audio pulses. Thus, the distance to an object should be perceived as being halved per doubling pitch.

(ii) <u>Perceived changes in pitch due to equal increments in the distance to an object</u>:

The fractional change in pitch $\Delta FR/FR$ corresponding to an equal change in the distance to an object (for example, one step toward an object) is shown in Fig. 6.6. The equal temperament pitch scale was used as a measure for the change in pitch. The fractional change in pitch is seen to be much larger at closer range than at farther range. As a result, the just noticeable change in the distance to an object is much smaller at closer range, being about 0.006m at 1m range cf. about 0.15m at 5m range (from a just noticeable change in pitch of a sustain train of pulses of 1 - 2 pps with rates of repetition up to 1000 pps)

It is interesting to compare the auditory cues for distance



CHANGES IN THE PITCH OF THE AUDIO PULSES
DUE TO EQUAL INCREMENT (0·5m) IN DISTANCE.

FIG. 6.6

perception of the SOS and other mobility aids, in particular, aids which also provide continuous indication of distance such as the Binaural Sensory Aid or the Sonic Torch. In the BSA, under dynamic conditon the frequency of the auditory stimulus, f(t), is a function of the distance to an object and the Doppler shift caused by the relative velocity between a user and the object. It is approximated by (Kay and Do, 1976):

$$f(t) = \frac{2m}{c}\,(D_o - v \times t) \quad + \frac{2v}{c}\,(f_2 - m \times t_s)$$

where m = rate of change of the transmitting frequencies

c = velocity of sound

D_o = initial distance to an object

v = relative velocity of a user to the object

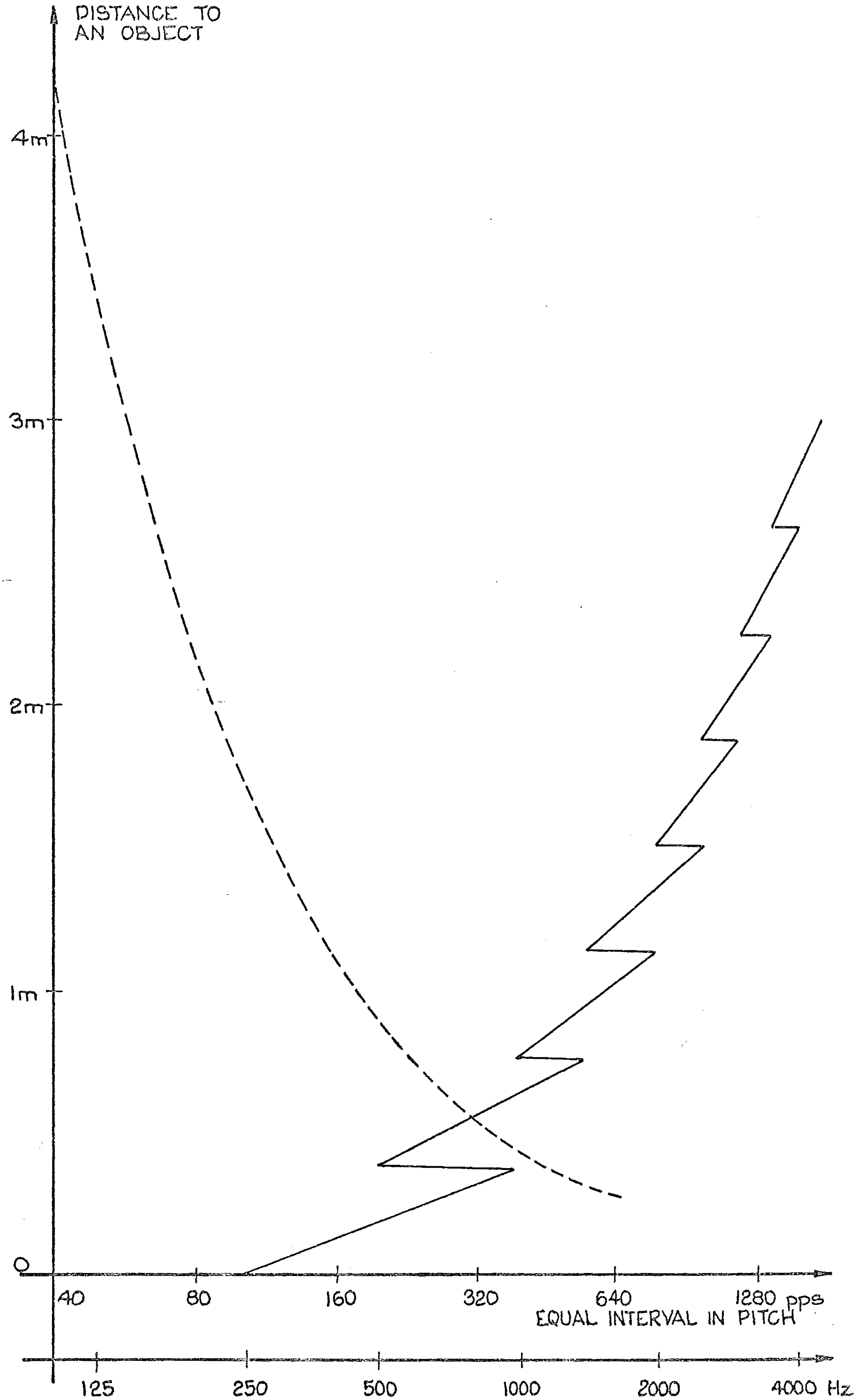
t = time

f_2 = upper limit of the transmitting frequency

t_s = frequency sweep time: $0 - T_s$; T_s = sweep period

Taking an approximate set of values to those used in the BSA: m = 200Hz/sec. T_s = 250msec. D_o = 3m f_2 = 100kHz; the frequency of the auditory stimulus produced when a user approaches an object with a constant radial velocity of 1.5m/sec. is shown in Fig. 6.7. Pitch of the stimulus is expressed in equal interval on the abscissa. The dashed curve represents the distance - pitch relationship of the SOS auditory stimulus.

Two differences are observed: (a) Pitch of the BSA stimulus increases with distance while that of the SOS decreases. (b) The pitch of the BSA stimulus varies in a complex zig-zag pattern while the pitch of the SOS stimulus varies in a much simpler pattern, being halved per doubling distance. The pitch of the SOS auditory stimulus is insensitive to the effect of



CHANGE IN DISTANCE TO AN OBJECT PER EQUAL INTERVAL CHANGE IN PITCH OF THE AUDITORY STIMULUS

- - - - IN THE SOS
——— IN THE BSA

FIG. 6.7

Doppler shift because the rate of repetition of the stimulus, FR = 343/D pps, is independent of the propagating frequency.

It is possible that the perception of the distance to an object can be easier with a simpler pitch - distance relationship. However, this has not yet been vigorously examined. The only objective comparison between the distance perception by the SOS and the BSA was made in a preliminary study by Brabyn (1978, p199). He compared locomotion control performances of subjects using simulated SOS and BSA auditory stimuli in a shorelining task (walking parallel, at a distance, to a row of objects). The comparison was made in terms of speed (AVSP), straightness of the path (RMSDSL) and proximity to the ideal path (RMSDIP). The results are tabulated in table 6.1. Although the results indicate that SOS subjects walked a little faster and closer to the ideal path, the evidence is inconclusive because the effect of Dopple shift has been omitted in the simulated auditory display of the BSA.

TABLE 6.1

Shorelining performance of inexperienced subjects (2 hrs practice)*

Aid / Performance index	SOS	BSA
AVSP	103.6cm/sec (17.5)**	92.3cm/sec(2.8)
RMSDSL	14.2cm (3.8)	12.9cm(5.2)
RMSDIP	28.4cm (14.4)	33.8cm(22.8)

* From Brabyn (1978).

** Standard deviation across subjects

6.4 LOUDNESS AS A DISTANCE CUE

Loudness has been argued to be the most likely source of information used in spatial perception by the blind (Curtis and Winer, 1969). It was found to vary in the same fashion as distance, reducing by 6dB per doubling distance (Warren, Sersen, and Pores, 1958). Also, a sound which was half as loud as a reference sound was judged as twice as far away (Steven and Guirao, 1962).

However, in existing electronic mobility aids, loudness was not given a strong emphasis as a natural distance cue, or ignored altogether. For example, in the Russell Path Sounder, the loudness cue was not employed, the amplitude of the auditory stimulus remains constant regardless of the distance to an object. In the BSA, although the loudness cue exists, the echo amplitude is reduced by about 12dB per doubling distance (due to spreading losses in the transmitting as well as in the returning path of the ultrasonic signal), which corresponds to a reduction in loudness much larger than the natural reduction of 6dB per doubling distance.

In the SOS, the use of an Equal Level Control Network (Section 4.3.2) allows the amplitudes of the echoes to be modified to assume any amplitude - distance profile. Therefore, with a suitable amplitude profile, it is possible to forge the loudness of the auditory stimulus to vary in a similar manner as the natural variation of loudness with distance. However, since the distance to an object is also determined by the pitch of the auditory stimulus, to be able to successfully determine a suitable amplitude profile, it is necessary to study the loudness - pitch characteristics of the SOS auditory stimulus. This was done by studying the equal loudness contours of the periodic pulses, which are, as mentioned earlier, an approximation of the SOS auditory stimulus.

6.4.1 <u>Equal loudness contours experiment; Introduction</u>

The loudness of a complex sound, such as periodic pulses, is believed to be a function of the number of critical bands excited by the sound frequency spectrum (Scharf, 1970) and their intercomponents masking (Scharf, 1959 a).

Several techniques were designed for calculating the loudness of a complex sound. They were described by Howes (1950), Zwicker and Feldtkeller (1955), Schneider, Wright, Edelheit, Hock and Humphrey (1972), Yeowart (1973), Warren (1973), etc... The most commonly-used loudness scales are the λ loudness scale designed by Garner (1959) and the Sone scale designed by Steven (1961). However, an experimental approach is preferred because of the scale validity (Garner, 1958; Steven, 1959) and its complexity (Garner, 1959).

A search of the literature revealed only the threshold of detection of periodic pulses experiment performed by Flanagan (1961), who measured the threshold contours for the periodic pulses of various pulse widths and at different rates of repetition. The following experiment extends Flanagan's work to equal loudness contour at the moderate listening levels anticipated with mobility aids.

6.4.2 <u>Procedure and apparatus</u>

The equal loudness contours were obtained by a loudness matching procedure.

Periodic pulse trains of pulse width 1 msec. and repetition rates (FR) between 20 and 860 pulses per second (test sounds) were matched in loudness to a reference sound of FR = 200pps. Three medium loudness levels of the reference sound were used, with root mean square sound pressure level (RMS SPL) at 53, 60 and 67dB.

Sounds were presented through a pair of KOSS Pro-A4 headphones. The reference and test sounds were presented alternatively, each lasted 1 second. There was a 1-second interval of silence after each sound. The 8 rates of repetition of the test sounds were tested randomly, four times each.

The subject was seated in an anechoic chamber with ambient sound measured at 25dBa SPL (using Bruel & Kjaer sound level meter type 2205). The subject controlled the loudness of the test sound by means of a 10-turn potentiometer. When the subject was satisfied that the reference and the test sounds were of the same loudness, he signalled the experimenter, seated in an adjacent room, by means of a control switch. After the voltage applied to the headphones was noted, another test sound of a different pulse rate was then presented. At the end of the experiment, the SPL corresponding to the noted voltages applied to the headphones were measured using Bruel & Kjaer artificial ear type 4152 and the audio frequency spectrometer type 2112. Measure was taken to compensate for the low sensitivity of the audio frequency spectrometer at low rates of repetition.

Eleven subjects participated in the experiment; all subjects were under 30 years of age and none reported any hearing anomalies. Five subjects had previous experience in psycho-acoustical testing.

6.4.3 Results

The mean equal loudness contours of 11 subjects are shown in Fig. 6.8 in terms of the RMS values of the SPL output from the headphones.

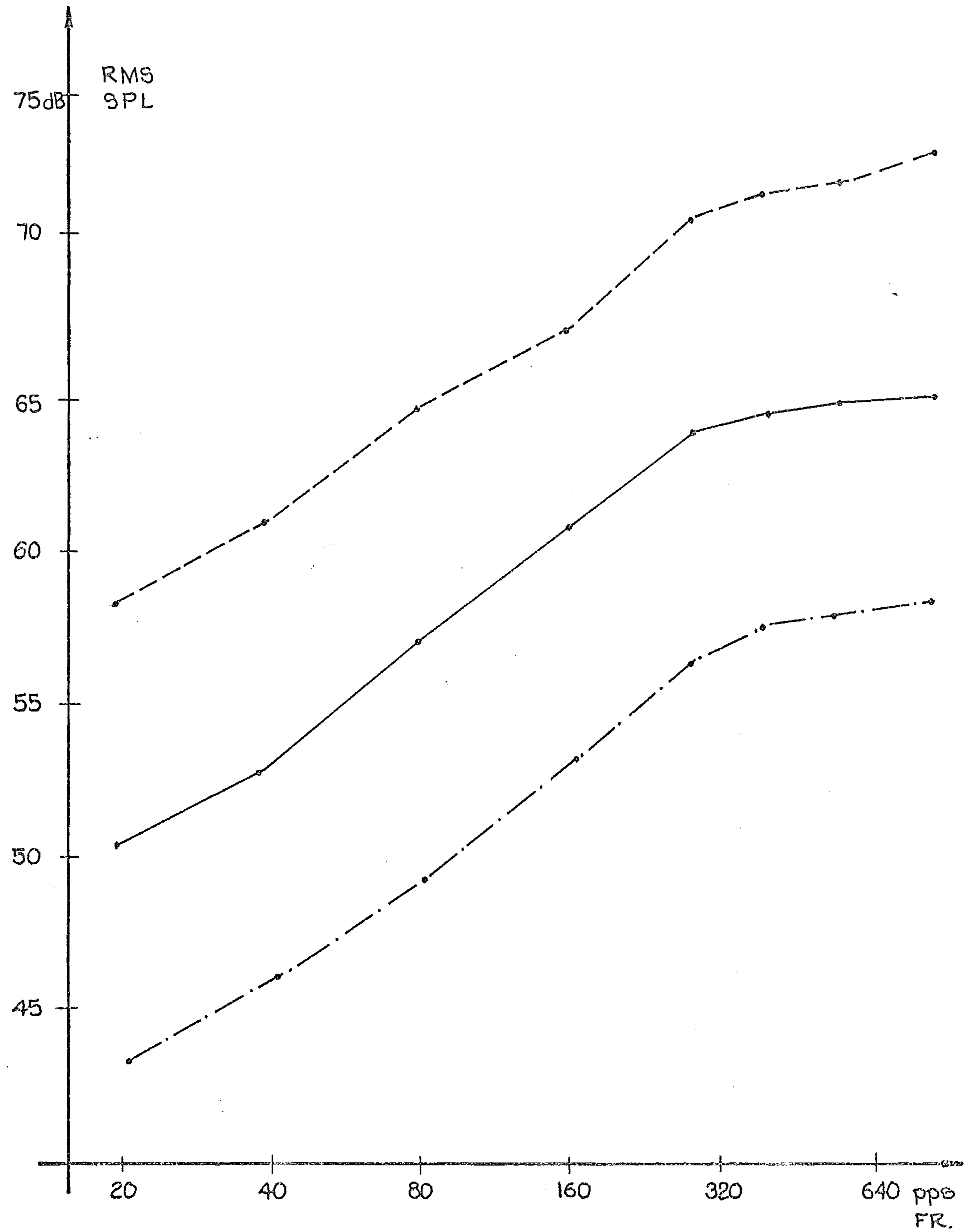
Since the reference sound was constant in level, an increase in the sound level of the test sound to achieve equal loudness implies a decrease in loudness of the test sound. The solid line in Fig. 6.8 shows that, at the reference sound level of 60dB, for equal loudness, the SPL of the test sound increases from 50dB at FR = 20pps to 63dB at FR = 400pps, or 3dB per an octave change in the rate of repetition. From FR = 400pps to FR = 800pps, the SPL of the test sound increases at a slower rate of about 2dB per octave.

6.4.4 Discusssions

The equal loudness contours will be considered in two parts; FR < 160pps and FR > 160 pps because, at 160pps, the separation of the frequency components is 160Hz, roughly equal to the minimum bandwidth of the critical band at low frequency (Scharf, 1970).

(i) FR > 160pps

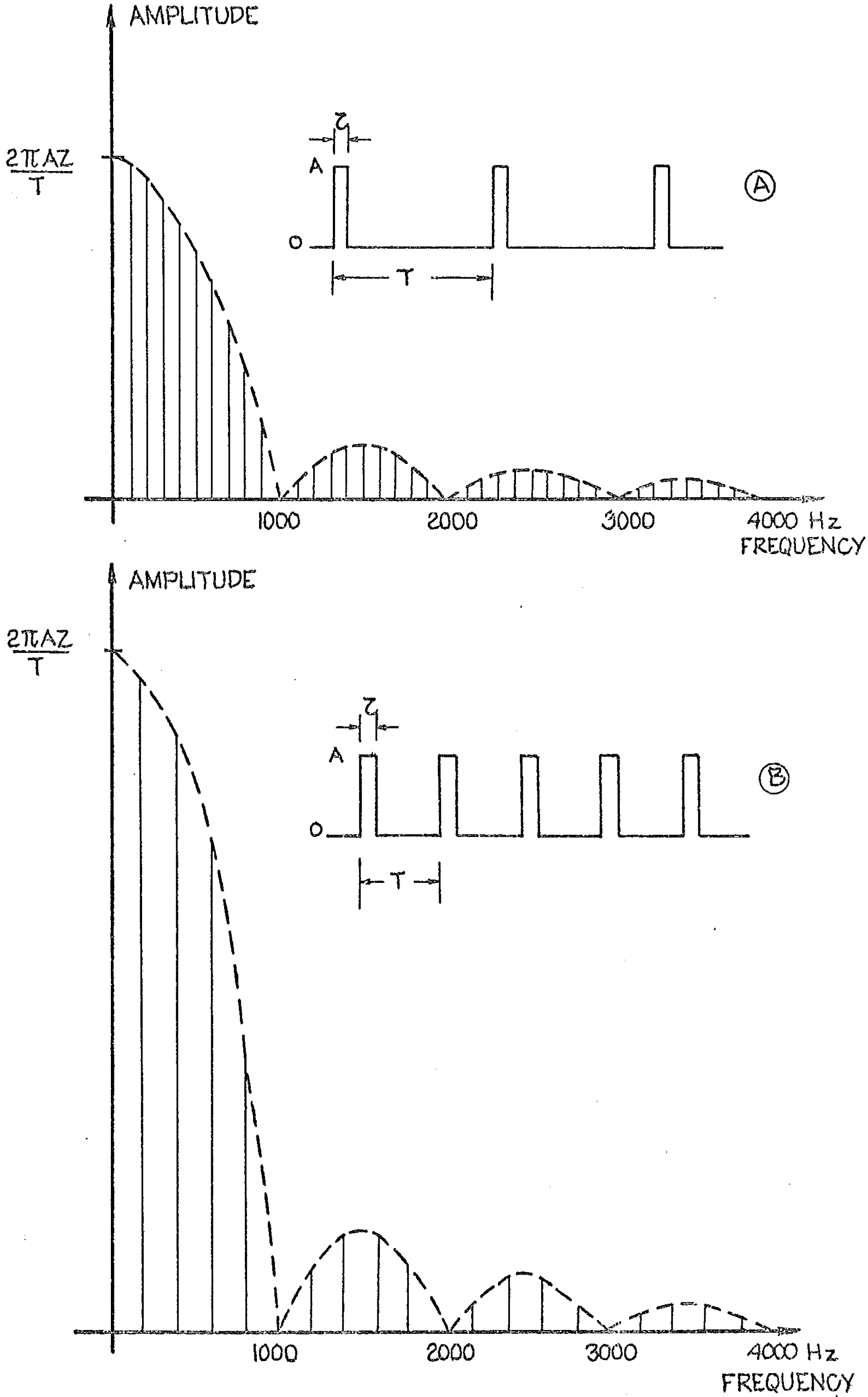
Fig. 6.9 shows the periodic pulses (FR_1 = 100pps and FR_2 = 200pps), together with their corresponding frequency components (1 msec pulse width). The separations of the frequency components are Δf = (FR)Hz. Thus, as the rate of



EQUAL LOUDNESS COUNTOURS OF PERIODIC PULSES.

REFERENCE SOUNDS AT 67 dB ------
60 dB ———
53 dB —·—·—

FIG. 6.8



FREQUENCY SPECTRUM OF PERIODIC PULSES

PULSE WIDTH τ = 1 msec

(A) FR $= \frac{1}{T} =$ 100 pps

(B) FR $= \frac{1}{T} =$ 200 pps

FIG. 6.9

repetition FR increases, the density of the frequency components in the sound spectrum decreases. Consequently, the number of critical bands excited by the frequency components is reduced (especially at low frequencies where the components are at higher amplitude). Since the loudness of a complex sound is believed to be a function of the number of excited critical bands, the loudness is expected to decrease with increasing rates of repetition. Quantitatively, the results of Fig. 6.8 reflect this fact.

However, the change in the rate at which the loudness decreased above 400pps could be explained in terms of the signal frequency spectrum and the number of excited critical bands. It is thought that the change in the loudness was partly due to the pleasantness of the sound. This hypothesis is explored in Appendix 7: Pleasantness of periodic pulses.

(ii) <u>FR < 160pps</u>

For FR < 160pps, the separation of the frequency component is less than 160Hz, the minimum critical bandwidth. Therefore, as FR decreases below 160pps, the number of excited critical bands cannot increase any further. Moreover, the intercomponent masking should increase due to the decrease in the separations of the frequency domponents. Thus, if the loudness of a complex sound can be solely accounted for by the the number of excited critical bands, the loudness should decrease as FR decreases. The equal loudness contours in Fig. 6.8 show a continuing increase in loudness and are, therefore, contrar to the above argument. Thus, it is possible that the number of excited critical bands is only one of the factors contributing to the loudness of periodic pulses. The pleasantness of the sound can be another factor:

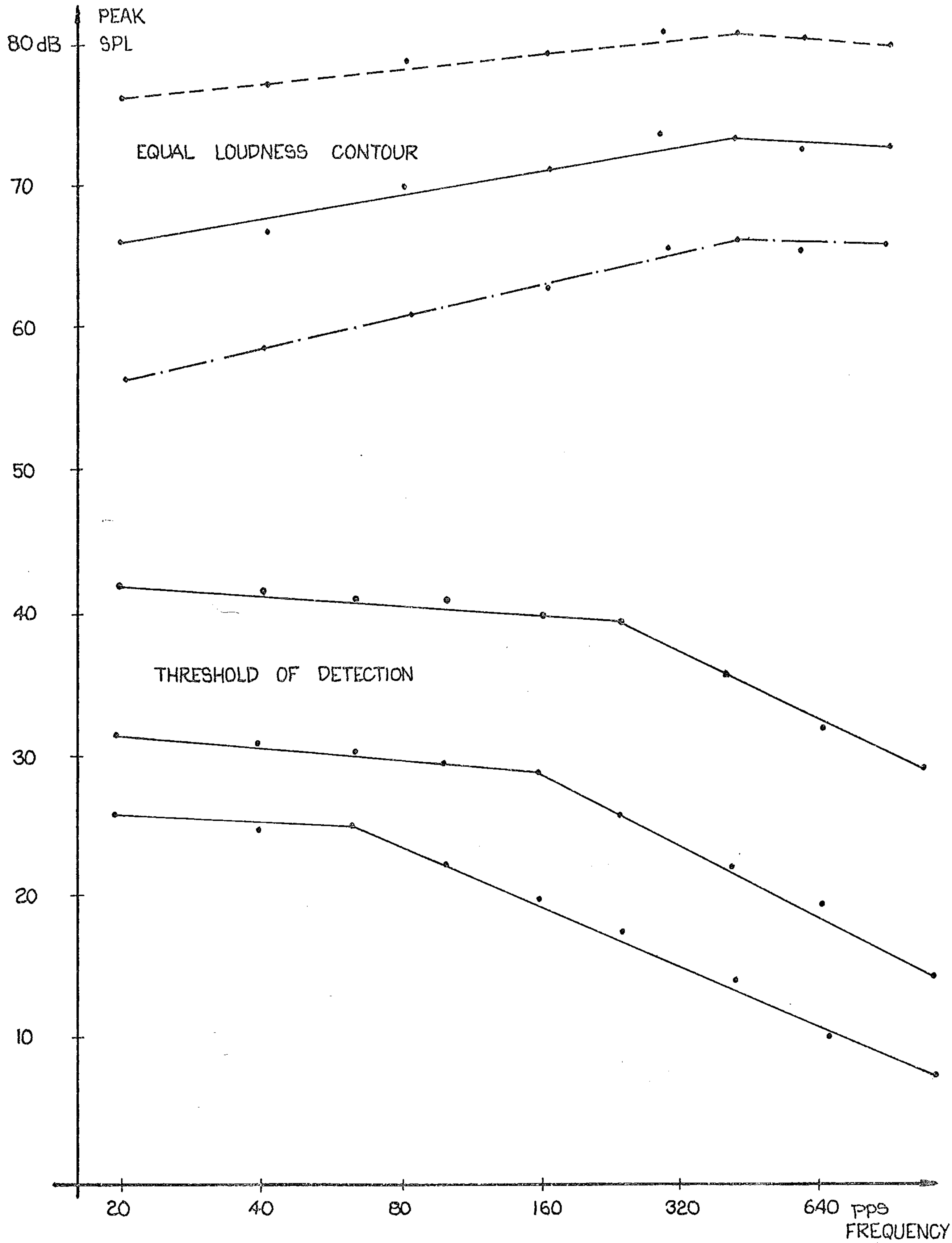
Subjects reported a general dislike for sounds at very low and very high rates of repetition. It is possible that at very low and very high FR, the sounds were not pleasant to listen to. This, in effect, might tend to induce the subject to reduce the SPL (and thus creates an apparent increase in loudness) to reduce the annoyance. As mentioned before, an attempt to prove this hypothesis is shown in Appendix 7.

(iii) General

The equal loudness contours are reproduced in Fig. 6.10, together with Flanagan's threshold of detection of periodic pulses. The equal loudness contours are expressed in peak sound pressure level, to be compatible with Flanagan's results.

It is seen that, as the rate of repetition increases, Flanagan's threshold of detection curves show a decrease in the threshold level, signifying an increase in loudness, while the equal loudness contours at 53, 60 and 67dB level, obtained from this experiment, show a decrease in loudness. Such differences in the shapes of the equal loudness contour and Flanagan's threshold of detection curves are, however, not unexpected. Equal loudness contours have been shown to depend on loudness levels. Scharf (1959b) found that, for a four-tone complex, as the number of excited critical band increases, the loudness increases for the tone complex at low sound pressure level and decreases for the tone complex at high sound pressure level.

In terms of distance perception, the equal loudness contours in Fig. 6.8 provided the necessary information to set up the



EQUAL LOUDNESS CONTOUR AND FLANAGAN'S THRESHOLD OF DETECTION FOR PERIODIC PULSES.

FIG. 6.10

equal level control network to provide either:

(a) A constant loudness regardless of distance. The advantage of having distance independent of loudness lies in the fact that in an ultrasonic mobility aid, the loudness also depends on the incident and reflecting angles of the ultrasonic signals and hence may not be a reliable distance due. The disadvantage is, of course, the reliance on an artificial coding for distance perception,

or (b) A loudness contour of doubling loudness per halving the object distance. The advantages and disadvantages are the reverse of those in (i).

The relative merits of these two types of loudness have not yet been adequately established and would be best determined in a controlled mobility study where performances of two groups of subjects using two types of loudness coding could objectively compared. Such an experiment is outside the scope of this thesis. In the prototype SOS, the equal level control network was set according to (i).

6.5 LOCOMOTOR CONTROL IN LABORATORY SETTINGS

As mentioned earlier, the completion of a computer-linked locomotion monitoring system at this University by Brabyn and his co-workers provided the opportunity to objectively and accurately measure the locomotive characteristics of subjects in a large mobility laboratory. Although the measurements can only represent the locomotion, and not mobility (as defined in Section 2.3) characteristics, they are thought to be important because they provide an objective indication of the subject's skill in controlling his movement through the environment. The latter has been considered to be an important subset of the overall mobility skills (Brabyn, 1978) and is a manifestation of the capability of a sensory aid in providing the spatial information necessary for locomotion.

In the following series of experiments, done in collaboration with Brabyn, the inventor of the locomotion monitoring system, the performance of an experienced SOS user were measured in a range of locomotor control tasks including shorelining, slaloming, walking around a circle, and circumnavigating unknown shapes. Wherever appropriate, comparisons were made with the performances of an experienced Binaural Sensory Aid user as measured by Brabyn. Performances of unaided, blindfolded subjects and sighted subjects were also included to serve as base line data.

6.5.1 Subjects

Since the aim of the experiment was to compare the upper limit of the aids capability, it was thought preferable to use experienced aid users.

Although the use of a number of subjects in each experiment would have been desirable, the lack of experienced aid users within the reach of this University (Brabyn, 1978, p130) and the difficulty in training subjects to be completely competent in using the aid (for example, the normal training period for a BSA user is 4 weeks), severely limit the number of available subjects. Therefore, the author, who has been using the SOS regularly for about 2 years, served as the sole subjects in experiments involving the SOS. Whereas, IP, who uses the BSA regularly for more than 6 years, served as the sole subject in the experiments conducted by Brabyn. It is worth noting that the lack of suitable subjects is a common problem faced by mobility researchers, and measures of mobility performances based on one subject are often encountered in mobility literature (Nye, 1971).

Six sighted subjects were used to obtain the unaided locomotive performances.

6.5.2 Experiment No. 1: shorelining with a row of poles

Shorelining with a row of poles (i.e., walking parallel to, and at a distance from the poles) was chosen to be the main locomotor control task because:

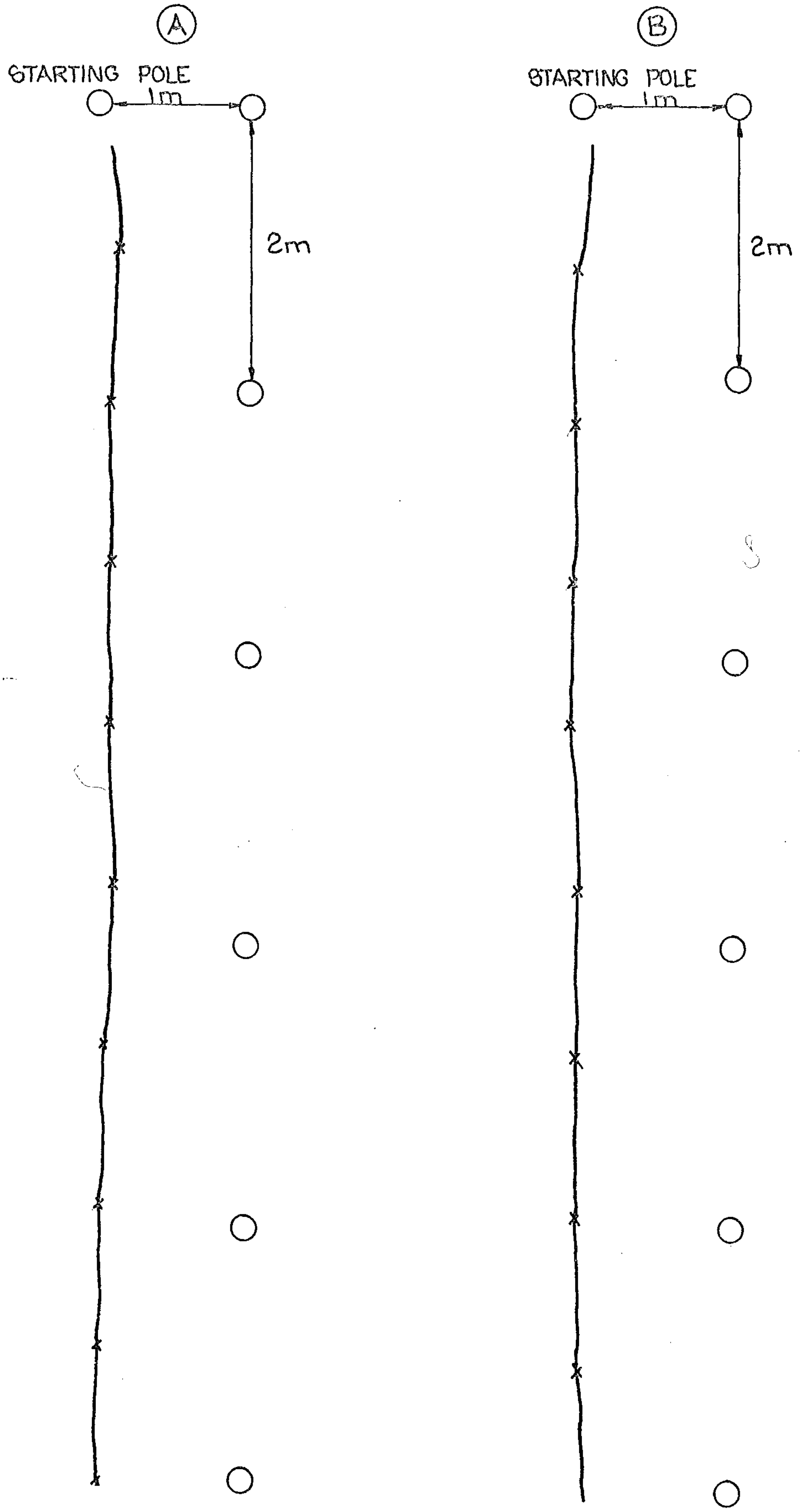
(a) shorelining is a common strategy that a mobility aid user often adopts when negotiating the environment. It is, in fact, one of the basic skills that BSA users are trained for.

(b) under laboratory conditions, numerical data about the movements of a subject can be accurately obtained and easily interpreted.

(i) Procedure

At the beginning of each trial, the blindfolded subject was guided to a starting pole place 1m from a row of six, 1.8m tall, poles. The poles were 2m apart (Fig. 6.11). The subject faced away from the row of poles. He was then asked to switch the aid on, turn round to face a direction parallel to the row, then walk parallel, at 1m distance, to the poles. He was told to stop 0.5m before reaching the last pole in the row.

The laboratory floor was carpeted and the walls were covered with ultrasound absorbent materials so that only the poles were detected by the aid.



TYPICAL PATHS IN A SHORELINING TASK OF
(A) A SINGLE OBJECT SENSOR USER
(B)+ A BINAURAL SENSORY AID USER

X : 1 SECOND SAMPLING INTERVALS
+ : FROM BRABYN (1978)

FIG. 6.11

(ii) Measurement

Several aspects of perforamnce could be obtained. The most relevant indicators were:

(a) Plot of the subject's path to provide a visual indication of smoothness and straightness of the path.

(b) The RMS deviation from the ideal path, RMSDIP. The ideal path was taken to be a straight line parallel to, and 1m from, the row of poles.

(c) The RMS deviation from a straight line, RMSDSL. Other measurements were also available such as average speed, etc. The average speed is not included here because although the variation of speed within a subject can be tentatively attributed to the difficulty of the control task, (i.e., a subject tends to walk slower in a more difficult task), no satisfactory explanation in terms of locomotor control has yet been advanced for the variation of the speeds across subjects.

(iii) Results and discussion

The plot of a typical path of the SOS user is shown in Fig. 6.11, together with that of an experienced BSA user. The plots indicated that locomotion was as smooth with the SOS as it was with the BSA. This observation can be substantiated by considering the RMSDSL and RMSDIP as tabulated in table 6.2. Together, they indicated that the SOS provided enough spatial information to enable the subject to maintain a comparable straight and accurate trajectory.

The usefulness of the SOS in controlling locomotion can be seen in perspective by comparing SOS performances with that of unaided, (i.e., using spatial memory only) blindfolded subjects and of sighted subjects. Their RMSDSL and RMSDIP values are tabulated in table 6.3. These values indicate that, as expected, performances with the SOS were inferior to that with vision. However, it is far superior to unaided performances. The latter comparison served as a positive indication of the usefulness of the aid in controlling locomotion in this shorelining task.

6.5.3 Experiment No. 2: Walking in slalom with a row of poles and around a circle

The shorelining task was valuable in providing a basis for numerical comparison between locomotions under the influence of different types of sensory inputs. However, the task did not seem to require a level of control as complicated as, say, in walking around a circle or in slalom with a row of poles. In walking clockwise around a circle, the direction of movement has to be changed clockwise at every step so that the total net angular change is 360°. While, in walking in slalom with a row of poles, there is a continuous angular change in the direction of movement, clockwise and anticlockwise, such that the net angular change between any two poles of the row is equal to zero. These two tasks can therefore be used to study the capability of the SOS in finer control of locomotion.

(i) Procedure

In the slalom task, the pole arrangement and the starting procedure were the same as in the shorelining task. The subject was asked to walk in slalom with the row of poles, at his normal speed. He was told to stop 0.5m before reaching the last pole.

Table 6.2: Performance in a shorelining task of SOS and BSA subjects

		SOS	BSA+
RMSDSL	mean	0.073m	0.077m
	SD++	0.030m	0.025m
RMSDIP	mean	0.181m	0.168m
	SD++	0.133m	0.070m

\+ from Brabyn (1978) ++ within S standard deviation

Table 6.3: Performance in a shorelining task of unaided, blindfolded subjects and sighted subjects

		Unaided	Sighted+
RMSDSL	mean	0.343m	0.034m
	SD++	0.185m	0.008m
RMSDIP	mean	0.879m	0.065m
	SD++	0.518m	0.018m

\+ from Brabyn (1978) ++ between S standard deviation

In the circle task, a 5m diameter circle was formed by an arrangement of eight poles (Fig. 6.13). The subject was asked to walk around the circle at 1m distance from the perimeter. He was told to stop when he completed the circle.

(ii) Results and discussion

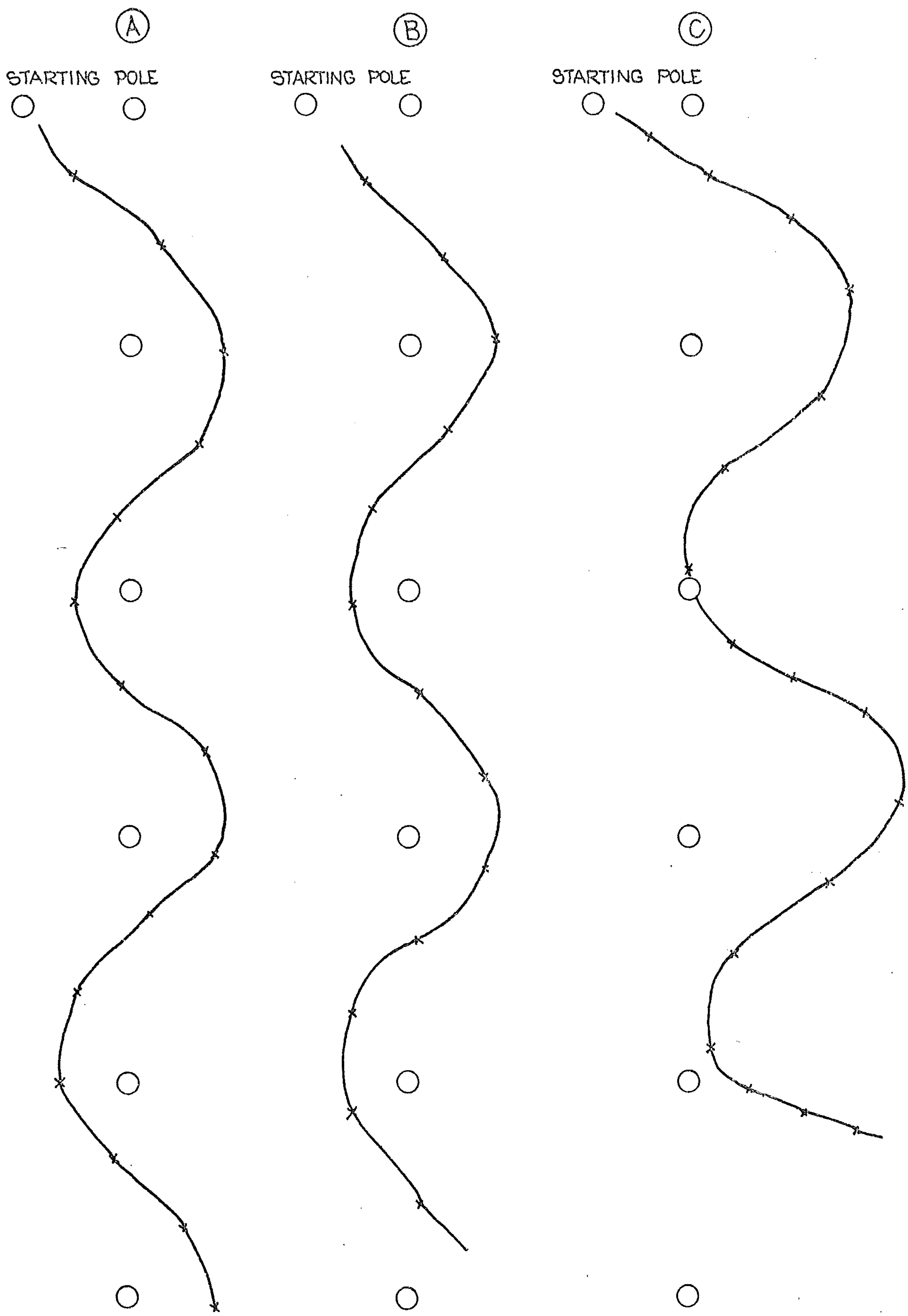
In these tasks, performances can only be judged from the plots of the subject's paths since a method of measurement to provide meaningful numerical data has not yet been devised.

Typical plots of the subject are shown in Fig. 6.12 and 6.13, together with the plots of the experienced BSA user and the plots of blindfolded unaided subjects (using spatial memory only).

It is seen that the SOS subjects performed the tasks smoothly and quickly. (The crosses indicate the distance travelled in 1 second.) As expected, control of locomotion was much better with the aid than with spatial memory alone. Again, performances of the SOS subject seemed to be comparable with that of an experienced BSA user.

6.5.4 Supplementary results

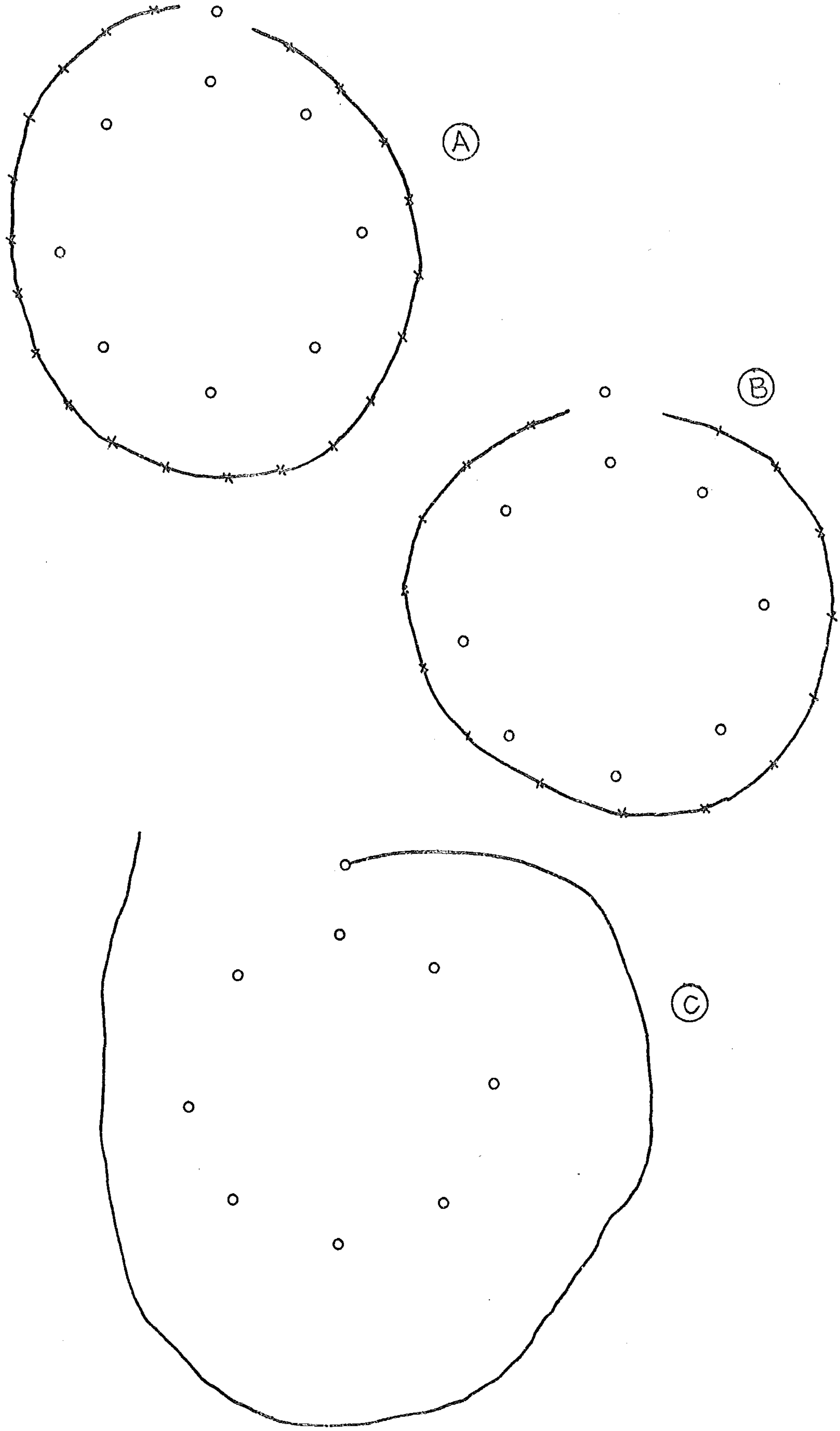
(i) In the above experiments, the subject was told in advance the exact nature of the task, such as shorelining, slaloming, or walking around a circle. The control of locomotion was, therefore, following a set pattern. For example, in the slaloming task, once the locomotion pattern for the first few poles was properly executed, no new change in the controlling of locomotion pattern was necessary. The subject can therefore safely execute the task following



TYPICAL PATHS IN A SLALOM TASK OF
Ⓐ A SINGLE OBJECT SENSOR USER
Ⓑ† A BINAURAL SENSORY AID USER
Ⓒ† A BLINDFOLDED & UNAIDED SUBJECT

X : 1 SECOND SAMPLING INTERVALS
† : FROM BRABYN (1978)

FIG. 6.12



TYPICAL PATHS IN A CIRCLE TASK OF
Ⓐ A SINGLE OBJECT SENSOR USER
Ⓑ† A BINAURAL SENSORY AID USER
Ⓒ† A BLINDFOLDED & UNAIDED SUBJECT

X : 1 SECOND SAMPLING INTERVALS
† : FROM BRABYN (1978)

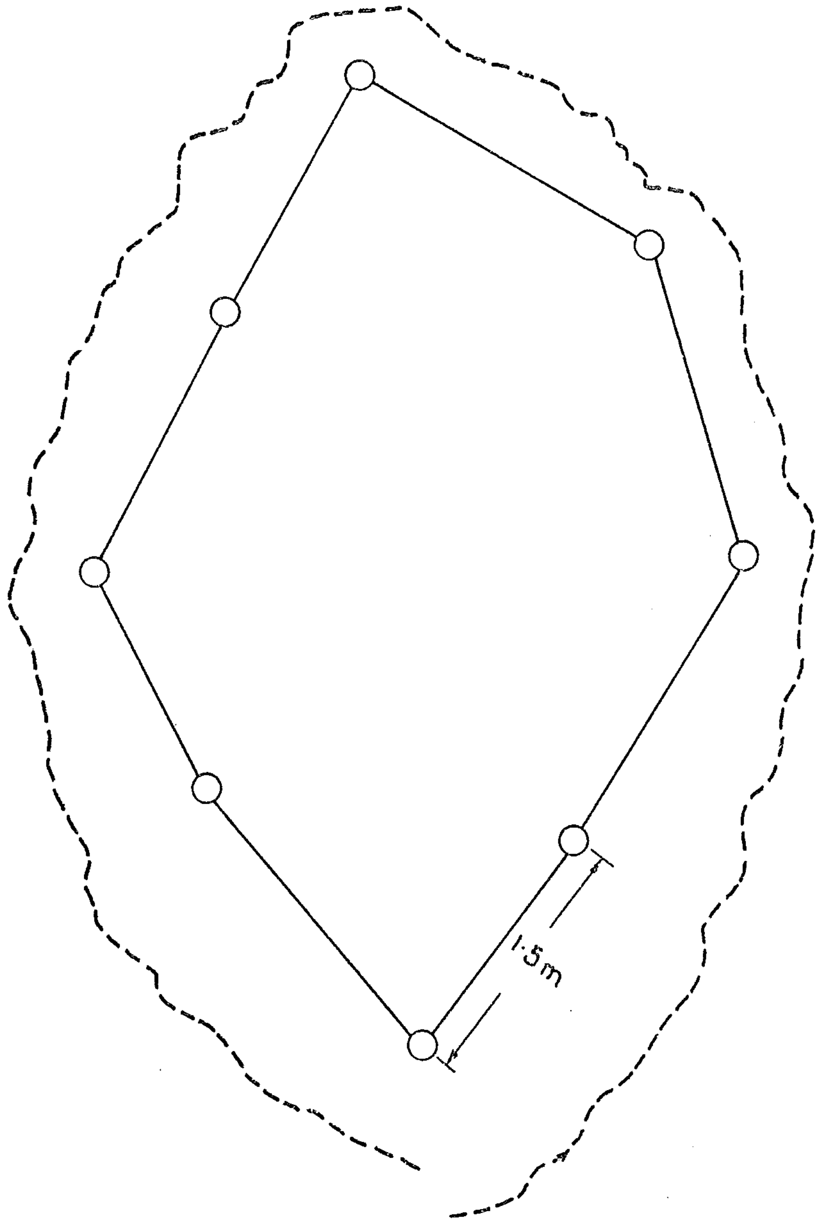
FIG. 6.13

the same pattern. In the following series of experiments, the subject was asked to circumnavigate a number of unknown figures. Since the subject did not have a prior percept of his trajectory, it is conceivable that he needs to rely more heavily on the spatial information provided by the aid to control his locomotion. The results of the experiment should, therefore, provide a stronger indication to the capability of the aid in providing the spatial information necessary for fine control of locomotion.

In the experiments, the subject was told to circumnavigate at a constant distance, to various unknown shapes made up by arrangements of poles, so that the poles were always on his left-hand side. Again, IP and the author served as the sole subject using the BSA and the SOS respectively.

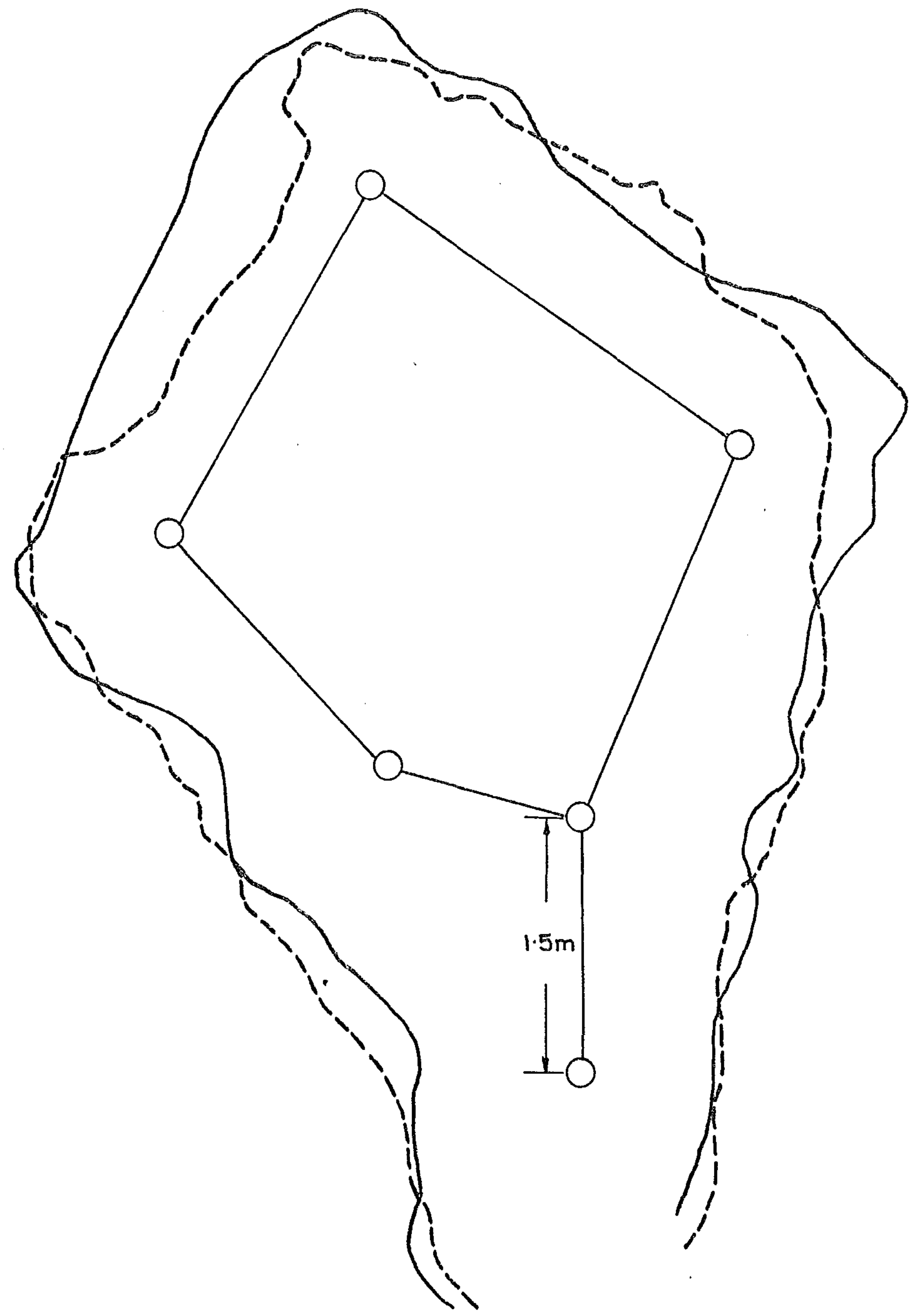
In general, the SOS subject was able to circumnavigate the unknown shapes reasonably well. A typical trajectory is shown in Fig. 6.14. Figure 6.15 shows the trajectory of the SOS subject and that of an experienced BSA user (IP) in another circumnavigating task. Both were able to perform it easily although it took the SOS subject more time to finish the task. (This is indicated by the roughness in the plot of his path). Again, although the difficulty in performing a task may influence a subject's speed, it is not yet well established whether the same conclusion can be drawn for variations in speed across subjects.

(ii) It is interesting to consider performance of the experienced BSA user in using the SOS. After a 10-minute familiarisation with the SOS, he was asked to use the SOS to:



TRAJECTORY OF THE SOS SUBJECT IN CIRCUMNAVIGATING AN UNKNOWN SHAPE.

FIG. 6.14



TRAJECTORY OF A SUBJECT IN CIRCUMNAVIGATING AN UNKNOWN SHAPE

- - - - - AN EXPERIENCED SOS USER

——— AN EXPERIENCED BSA USER

FIG. 6.15

(a) shoreline with a row of poles.

(b) walk between two rows of poles.

(c) circumnavigate unknown shapes.

He was then asked to repeat (c) using the BSA. To disorientat him, the starting position in (c) was changed, although the same shapes were retained.

The results are shown in Fig. 6.16 and Fig. 6.17. They indicated that, even with only 10-minute familiarisation, the subject was able to perform the task accurately and with ease. In the circumnavigating unknown figures task, the plots indicated that the performances with the SOS were comparable with the subject own aid.

6.5.5 Conclusion

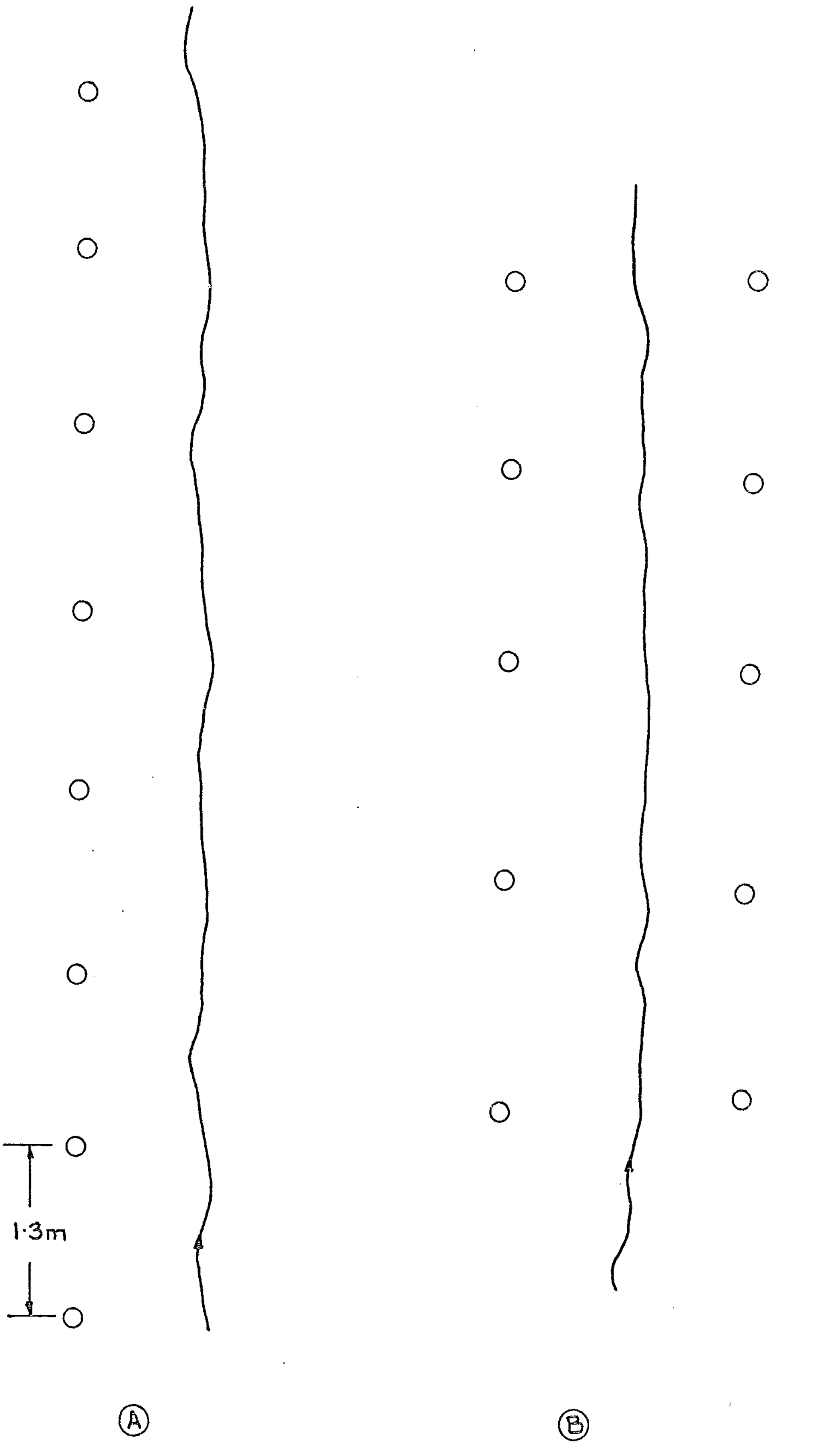
The results from the above experiments were obtained from an experienced Single Object Sensor user; therefore, they should be considered as the upper, rather than the average, level of performance.

For the shorelining task, the results are summarised in Table 6.4 which includes the results of "inexperienced" subjects using the computer-simulated display of the SOS already mentioned in Section 6.3. From these results, it can be concluded that:

(i) Even "inexperienced" subjects were able to use the spatial information provided by the SOS for fine and smooth control of locomotion.

(ii) Although performances improved with practice , they were as expected, inferior to sighted performances.

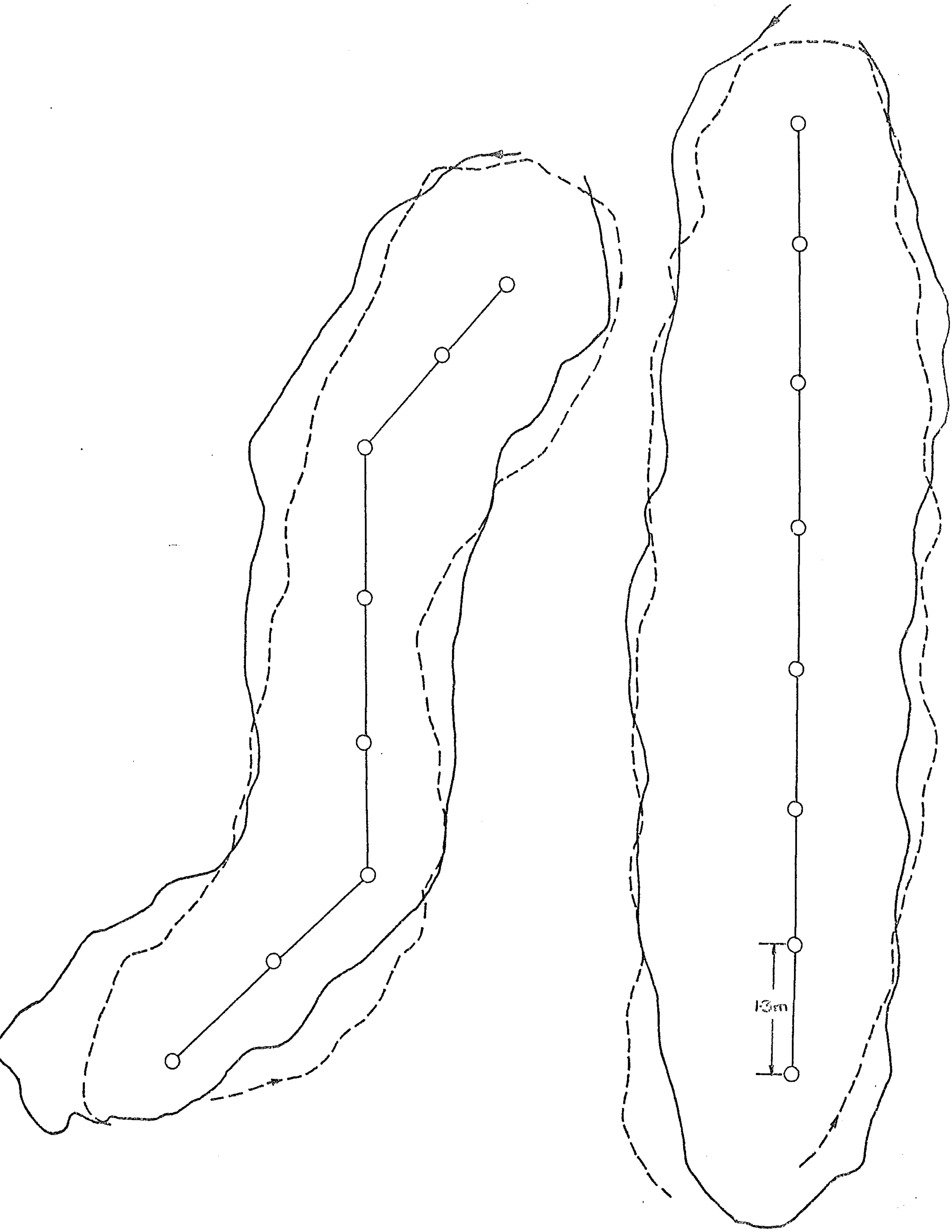
(iii) At the upper level of performance, the SOS is comparable with the BSA, a well-established mobility aid, in



TRAJECTORIES OF AN EXPERIENCED BSA USER USING THE SOS IN

(A) A SHORELINING TASK
(B) WALKING BETWEEN TWO ROWS OF POLES

FIG. 6.16



TRAJECTORES OF AN EXPERIENCED BSA USER IN CIRCUMNAVIGATING AN UNKNOWN SHAPE.

– – – USING THE SOS

——— USING THE BSA

FIG. 6.17

shorelining with a row of poles in a laboratory setting.

The results of "inexperienced" subjects using the computer-simulated BSA as mentioned in Section 6.3 are not included here because it is thought that, due to the omission of the Doppler shift and the reduction of the number of detected objects to one (Brabyn, 1978), the auditory stimulus of the BSA has not been realistically simulated.

Performances of the SOS subject in circumnavigating unknown shapes further demonstrated that the SOS was providing enough spatial information for fine and smooth control of locomotion in a laboratory setting.

Table 6.4: Summary of performances in a shorelining task

Measurements \ Subjects		Unaided	"Inexperienced" SOS	"Experienced" SOS	"Experienced" BSA	Sighted
RMSDSL	mean (m)	0.343	0.142	0.073	0.077	0.034
	SD (m)	0.185+	0.038+	0.030++	0.025++	0.008+
RMSDIP	mean (m)	0.879	0.284	0.181	0.168	0.065
	SD (m)	0.518+	0.144+	0.133++	0.070++	0.018+

\+ across subject SD ++ within subject SD

6.6 GENERAL CONCLUSION

The study described in this chapter provided some basic information about the spatial perception with the Single Object Sensor in a controlled environment.

The study showed that the perceived distance was halved per doubling pitch and that loudness of the auditory stimulus was not a linear function of pitch.

In the locomotor control field, smooth control of bodily path with the SOS was shown to be possible in a number of locomotor control tasks, ranging from a simple shorelining task to a more demanding job of circumnavigating unknown shapes. Performances were also shown to be comparable with that of the Binaural Sensory Aid. However, it should be noted that the reported experiments were restricted to a controlled environment where the objects were simple poles and the spatial information was provided solely from the sensory aid used. The performances, therefore, may not be representative of that in the real environment where objects have many different shapes and sizes and where numerous natural cues are available. Nevertheless, the above study formed a first step towards establishing, objectively, the usefulness of the SOS in locomotion which has been considered as an important subset of the mobility skills.

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CHAPTER 7

ON THE USE OF THE SINGLE OBJECT SENSOR AS A MOBILITY AID

7.1 INTRODUCTION

The use of the Single Object Sensor as a sensory aid in a laboratory setting has been examined in the previous chapter. Although the laboratory setting provided an opportunity to study the aid objectively and in a controlled manner, the success or failure of an aid lies on its usefulness in the real environment. Mobility in the real environment, as indicated earlier, involves not just locomotion, but also orientation toward landmarks in which the ability to recognise objects is an important prerequisite.

This chapter addresses the problem of object recognition and describes a method suitable for evaluating a mobility aid.

Objects in space have many shapes and sizes and are made from a variety of substances. Therefore, they affect differently the reflection of ultrasonic signals (the sonar signature). Hence, the "vocabulary" of the aid "language" is more extensive than that obtained in a laboratory setting. The factors influencing the sonar signature of the objects are analysed in the first part of this chapter. The recognition of some commonly encountered objects is then studied.

Because mobility is a complex, dynamic process involving the translation of sensory information into effective motor movement, evaluation of a mobility aid is a many-faceted problem. The difficulties involved in an evaluation process are presented in the second part of the chapter. It is argued that a comprehensive evaluation process would involve an enormous amount of time and manpower and is therefore outside the scope of this thesis. As a substitute, the mobility process is analysed and broken down into sets of subskills (Section 7.5). Suggestions as to the usefulness of the aid in these subskills are then given, together with possible rationales. Although the treatment falls short of an objective evaluation, it is hoped that the suggestions form a first step toward understanding the aid and provide useful information on which future evaluations can be based.

7.2 THE SONAR SIGNATURE

Most objects commonly encountered in the environment can be considered as complex objects whose surface gradients change abruptly across the reflecting surface; for example, trees, bushes, cycle stand, shop front, etc.

The echoes from a complex object are not only a function of the incident angle and the propagating frequency, but also a function of the structural formation of the reflecting surface. Various methods have been designed to predict the echo amplitudes from complex objects (e.g., Deryugin, 1952; Ando and Kato, 1976; Johnson, 1976). These methods usually require the integration of the echoes over a unit area. Therefore, they are applicable only to objects with periodically uneven surface (e.g., lapped fence) and cannot be easily extended for calculating the reflection from unperiodically uneven surface (e.g., rough stone wall, trees). The reflections of ultrasonic signals from complex objects were, instead, studied by recording the sonar signature or the envelopes of the ultrasonic echoes (i.e., the audio pulses). Under dynamic condition, two phenomena were observed: Amplitude and Time jitters. They are, in part, peculiar to the Single Object Sensor:

7.2.1 The amplitude jittering effect

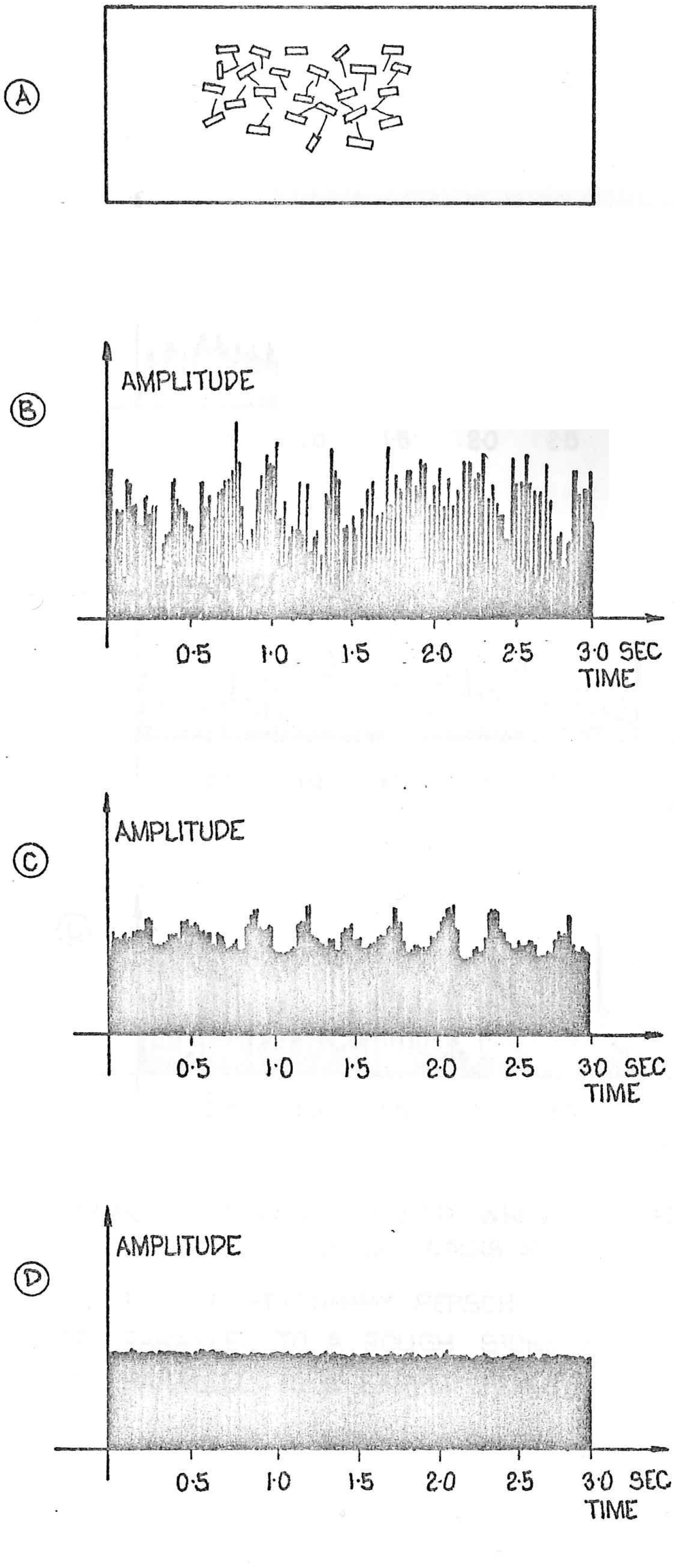
Since the surface gradient of the reflecting surface of a complex object changes abruptly under dynamic condition, the incident and the reflecting angles of the ultrasonic signals fluctuate widely. As a result, fluctuation in the echo amplitudes is observed. This effect can be vividly demonstrated by recording the sonar signature of an artificial tree at 3m distance from a radiating source. The leaves of the artificial tree were made of cardboard with a density of two leaves per cm^3 (fig. 7.1a). The leaves were at random angle to the tree axis.

Fig. 7.1b shows the sonar signature of the tree immediately after shaking it. A violent fluctuation in the sonar signature (up to 6.5dB change in pulse to pulse amplitude) due to a rapid change in the incident and reflecting angles of the ultrasound was observed.

Fig. 7.1c shows the sonar signature of the tree 1 minute after the initial shake. The magnitude of fluctuation was reduced considerably due to a more gentle movement of the leaves and hence a smaller change in the incident angles of the ultrasonic signals.

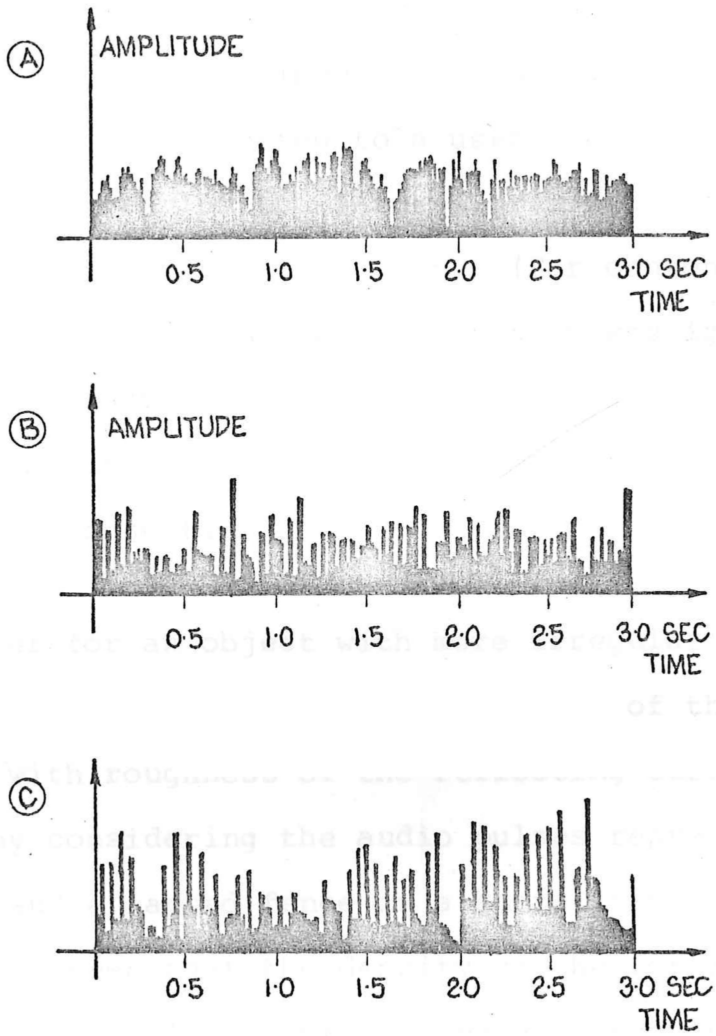
Fig. 7.1d shows the sonar signature of the tree 3 minutes after the shake. No noticeable fluctuation in echoes amplitude was observed. In this static condition, the sonar signature of a complex object is similar to that of a simple pole.

The sonar signature of some other complex objects (a pedestrian, a rough stone wall, and a lapped fence) are shown in Fig. 7.2.



Ⓐ AN ARTIFICIAL TREE.
Ⓑ SONAR SIGNATURE OF THE TREE IMMEDIATELY AFTER SHAKING.
Ⓒ SONAR SIGNATURE OF THE TREE 1 MINUTE AFTER SHAKING.
Ⓓ SONAR SIGNATURE OF THE TREE 3 MINUTES AFTER SHAKING.

FIG. 7.1



SONAR SIGNATURES PRODUCED WHEN A USER OF THE SINGLE OBJECT SENSOR WALKS AT A SPEED OF 1m/sec

Ⓐ PAST A STATIONARY PERSON.

Ⓑ PARALLEL TO A ROUGH STONE WALL.

Ⓒ PARALLEL TO A LAPPED FENCE.

FIG. 7.2

7.2.2 The time jittering effect

The fluctuation in the echo amplitudes can also produce a jittering effect in the periods of the echoes: Due to the amplitude jittering effect , there can be instants when an echo is below the preset threshold level (Section 4.3.2). In these cases, no audio pulse is presented to a user; the next possible echo can only be received 16msec. later (for a 2.5m range device). The period of the echoes is thus given by: (For convenience, the effect of the user speed on the echo period was ignored)

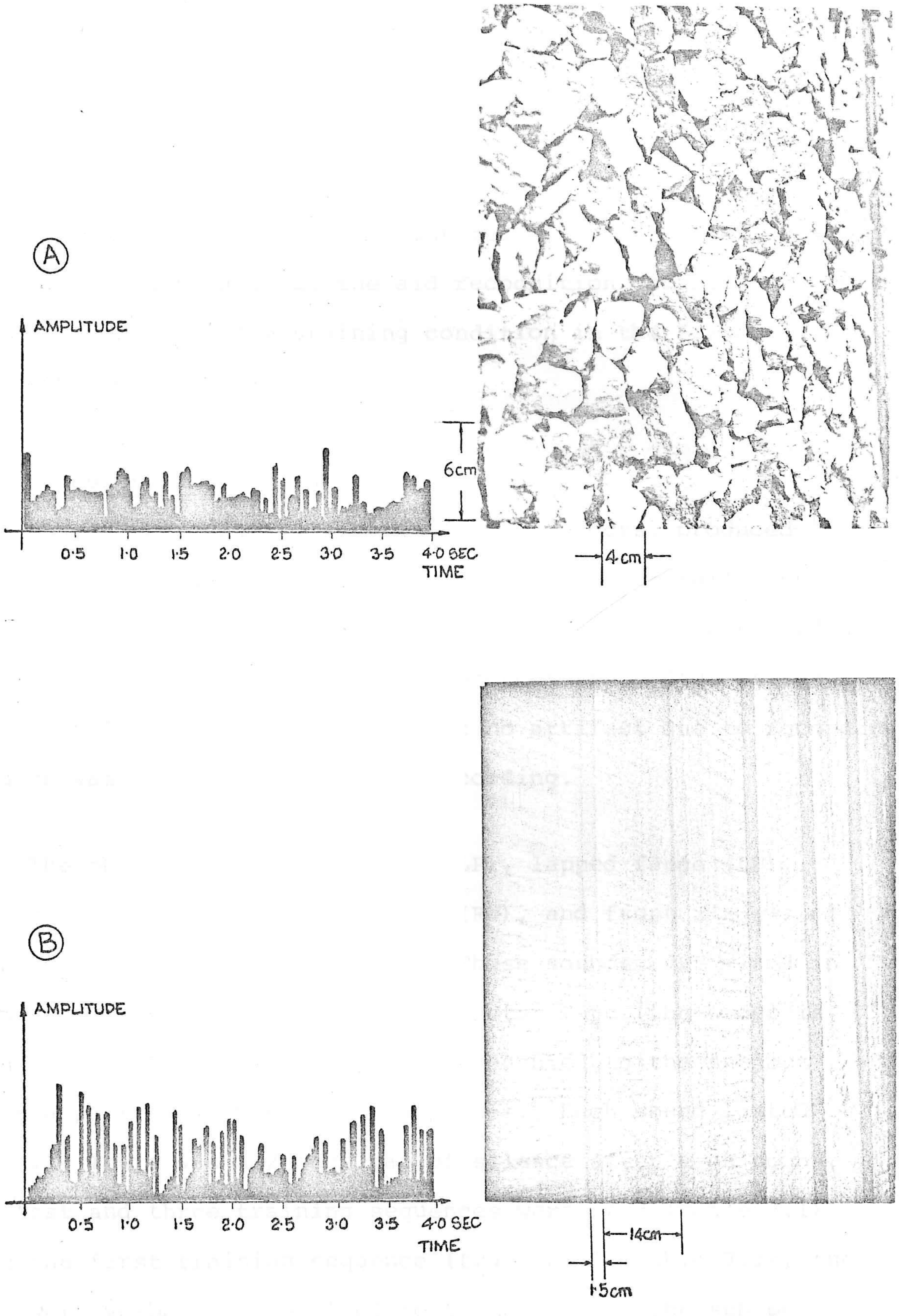
$$T_{n+1} = T_n \pm k_{n+1} \times 16 \text{ msec.}$$

where k is a probability constant depending on the structural formation of complex object.

k is smaller for an object with more irregularities on the reflecting surface. In other words, the density of the audio pulses increases with roughness of the reflecting surface. This can be observed by considering the audio pulses representing a rough stone wall and a lapped fence in a shorelining task as shown in Fig. 7.3 It was seen that the density of the former was higher than that of the audio pulses representing a lapped fence due to the more irregular reflecting surface of the stone wall.

7.3 RECOGNITION OF SOME COMMONLY ENCOUNTERED OBJECTS: AN EXPERIMENT

As mentioned, the jittering effects on the amplitude and on the rate of repetition of the audio pulses are the main features used to differentiate objects. However, in a real environment, the upper limit of the recognition capability of a user depends not only on the threshold of jittering detection, but also on his knowledge of the immediate environment.



THE AUDIO PULSES PRODUCED WHEN A SINGLE OBJECT SENSOR USER SHORELINES, AT SPEED OF 1m/sec, WITH

Ⓐ A ROUGH WALL

Ⓑ A LAPPED FENCE

PICTURES OF THE OBJECTS ARE SHOWN NEXT TO THEIR REPRESENTING AUDIO PULSES.

FIG. 7.3

The recognition capability can conceivably be improved with prolonged practice, thus making a study of the upper limit outside the scope of this thesis. On the other hand, a study on the recognition of some commonly encountered objects is useful in providing some notion about the aid recognition capability. This is examined under a minimum training condition in the following experiment.

7.3.1 Procedure and apparatus

Sounds representing five different objects, produced when the Single Object Sensor was moved past, or parallel to, the objects at a normal walking speed of 1m/sec., were recorded on magnetic tape using a UHER tape recorder (type 4400 stereo). Extreme care was taken to ensure that no artifact due to recording procedure was introduced into the recording.

The objects were; lamp post (LP), lapped fence (LF), row of trees (RT), rough stone wall (RW), and front windows of the shops in a shopping mall (SF). These sounds were mixed in random order, then transferred to a master tape (the order is tabulated in table 7.1). They were presented to the subject through a pair of KOSS Pro A4 headphones. Each sound lasted 20 secs. There was a 2 sec. gap of silence after each sound. Three test and three training sequences were used (Table 7.1). During the first training sequence (training 1, table 7.1), the sounds were verbally identified to the subject. The subject was then asked to verbally identify the sounds in the remaining test and training sequences. Feedback was given only in the training sequences.

Nine subjects with no previous experience with the Single Object Sensor participated in this experiment. The experiment lasted about 10 minutes for each subject.

7.3.2 Results

The results were computed from the responses in the test sequences only. They are shown in Fig. 7.4 In the first test sequence, the responses correlated 0.74 with the correct sounds (Pearson Product-Moment-Correlation) and most of the confusions were between lapped fence and rough stone wall. The response improved in the second test sequence, with the product-moment-correlation coefficient being 0.98 and again the confusions were between lapped fence and rough stone wall. Almost 100% correct response was recorded in the third test sequence, the responses correlated 0.984 with the correct sounds.

Table 7.1: Object recognition experiment: Order of presentation

Training 1	LP	LF	RW	RT	SF
Test 1	SF	RT	LF	LP	RW
Training 2	LP	RW	LF	SF	RT
Test 2	LP	SF	RT	LF	RW
Training 3	RW	SF	LF	LP	RT
Test 3	RT	LP	LF	RW	SF

True Reported	LP	LF	RW	RT	SF
LP	+++++++++ ooooooooo #########				
LF		++ oooooo ########	+++	+	
RW		+++++++ ooo #	++++++ ooooooooo #########		
RT				++++++++ ooooooooo #########	
SF					+++++++++ ooooooooo #########

Fig. 7.4: Responses in the object recognition experiment.
+: test 1 o: test 2 #: test 3

7.3.3 Discussion

Sounds representing lamp posts, trees, and front windows of the shops can be recognised immediately. Sounds representing a lapped fence and a rough stone wall, although a little confusing at first, can be recognised after very little training.

The result indicates that some commonly-encountered objects can be recognised quickly and easily using the SOS. There was no direct comparison of the recognition capability provided by the SOS and other mobility aids. A search of the literature revealed only the time required to recognise six types of fences in the training of the Sonic Torch (Sharpe, undated). Sharpe noted that the average time used by Sonic Torch user to recognise six types of fences was about 2½ hours. Since the objects used in the two conditions were different, a comparison of the two results would not be meaningful .

Although finer discrimination of objects can be possible (sound representing certain types of tree were found to be distinguishable when presented sequentially to a subject); the types of object readily recognisable by the Single Object Sensor are limited. Corrugated iron fence and lapped fence, while can be recognised (with training) using the Sonic Torch or the Binaural Sensory Aid, may not be easily distinguishable from the sounds produced by the SOS. The relatively low recognition capability of the SOS in comparison with the BSA is inherent in the design of the SOS. The reason being that the information capacity of a transmission system is proportional to the bandwidth of the receiving channel. The 3dB bandwidth of the receiving system in the SOS is only about 2 KHz compared with 40 KHz in the case of the BSA.

7.4 EVALUATING A SENSORY AID

Evaluating a mobility aid is a complex multi-faceted problem. While the physical aspects of the aid such as reliability, cost, can be objectively determined, the psychological aspect, namely the usefulness of the device as a mobility aid can not be easily resolved. Before going further to find out why this could be seen as a difficult task, let's have a look at the evaluations attempted so far and their results.

7.4.1 Main Evaluation Programs

Many attempts have been made to provide the information about the usefulness of mobility aids. They ranged from a single subject trail (Curtis, 1971), to an elaborate evaluation program involving hundreds of blind persons in many mobility centres around the world (Kay, 1973 a). While many evaluation programs are designed specially for a particular aid, such as the evaluation of the Swedish Laser Cane by Jansson (1975, 1977), others are broadly designed and can be used for more than one type of aid. Fundamentally, the latter falls into two main categories:

In the first one, mobility was divided into a progressive list of sub-skills such as detecting obstacles, travelling in familiar environment. Performances of a user in these sub-skills were then assessed. This was first originated by Wright and put forward by Leonard and Wycherley (1967) as the first serious attempt at evaluating a mobility aid.

The list was refined and used extensively to form a check list in the evaluation of the Binaural Sensory Aid (Kay 1973 b). The subjective impressions of the mobility instructors on how a blind trainee performs these tasks formed a great part in this evaluation. Not surprisingly, as a consequence, a number of diverse opinions was produced with no firm backing data (Ward 1973; Murphy, Johnson, Healey and Kenji, 1973; Thornton 1973), although most trainers considered the mobility of the BSA users to have improved (Airasian, 1973).

The evaluation of the Laser Cane (Nye, 1973) followed the similar line. Apart from the subjective impressions of mobility teachers about the specific subs-task on the checklist,the evaluation was supplemented by records of the number of "critical events" such as body contacts, hesitations, etc. Although marginal improvement in mobility was thought possible, no firm conclusions were made due to insufficiently reliable data.

In the second category, mobility was divided into three functional classes: safety, efficiency and stress. Mobility performances were then assessed according to these criteria. This was a serious effort by the Blind Mobility Unit at Nottingham to render evaluation more objective (Armstrong, 1972, 1973, 1974). In this technique, safety was measured in terms of the number of collisions with objects, accidental veering from the footpath, etc. Efficiency was measured by, among other things, the productive walking index (the proportion of time spent in actual locomotion versus total travel time). Stress was measured in terms of the average stride length. This technique was used in the evaluation of the Nottingham obstacle detector and to some extent the Binaural Sensory Aid.

The technique represents a step forward in objectively measuring mobility. It provides valuable data on several aspects of mobility. However, it does not indicate the proficiency of of a user in specific mobility activities such as the ability to follow a footpath bordered by hedgerows, or finding a kerb, etc. The overall indication of mobility activities is important in indicating the type of activities and environments which the aids are particularly useful for (such as indoor, in uncrowded environment or a busy downtown area). This information is valuable because it allows a blind person to choose an aid suitable for his need and for the environment that he frequents most.

7.4.2 Difficulties involved in evaluating a mobility aid

It is apparent that no mobility evaluation programs have been universally accepted. The reasons are numerous. First of all, an evaluation process requires a basis for comparison. Although such a basis can be easily stated, that is sighted mobility (Leonard, 1973), identifying the variables of sighted mobility is a difficult task. The variables are difficult to define and isolate (Nye, 1971) because mobility is a complex dynamic process and highly interactive with the surrounding environment.

Even if the variables can be isolated, measuring them objectively is not an easy matter (Leonard and Wycherley, 1967). For example, how does one measure the psychological stress? Although heart-rates have been used successfully to measure stress in car driving, it was found to be an ineffective means to measure stress in blind mobility (Heyes, Armstrong, Williams, 1976). The use of secondary tasks as a means to measure the surplus mental capacity, while using the sensory aid, was suggested as an alternative (Nye, 1971). However, the result from this technique is not yet well documented. Measures of stride length have also been suggested as another means to determine the stress (Armstrong, 1974). However, conclusive evidences linking the psychological stress and stride length have not yet been well supported.

Secondly, the evaluation requires an assessment of a man-machine combination, therefore it involves many complex variables. For example, the success or failure of an aid depends not only on the information provided by the aid but also on the user's ability to process it as well as the way the information is introduced.

Screening of potential users (Leonard and Wycherley, 1967) to reduce the variance of performance highlights an attempt to eliminate one of the variables. On the other hand the debate of whether the BSA should be taught at the same time as, or after, the Long Cane, highlights another problem that an evaluation program should be looked at so as to provide meaningful results.

Then there is the problem of attributing the improvement of mobility performance to the correct source; that is, to determine whether the improvement is due to the aid being used or just because of more experiences are being accumulated, and to isolate the reason for the success or failure of the aid so that such failures are not repeated in future development. For example, is the ability of a user to recognise a particular object due to the spatial information provided by the aid or due to his knowledge of the environment? Or is it a combination of both? Will an aid with less detailed spatial information enable him to recognise the same object?

These uncertainties and many more difficulties encountered in the evaluation, have made it an art rather than an exact science. As a consequence, most of the evaluation programs so far have resulted in informed opinions rather than firmly based conclusions.

7.4.3 Possible Schematic of an evaluation program

From the above discussion, it is apparent that a meaningful evaluation program needs to assess the usefulness of an aid in helping a blind person to carry out the mobility activities in a safe and efficient way. The prerequisite for this would be the establishment of standard activities, as well as means of measuring the characteristics of the activities in an objective way. Standard mobility activities can be defined along the line advocated by Leonard and Wycherley and may need to have the concensus of mobility experts, while the measurement can be carried out using the criteria developed by Armstrong and Jansson with the help of video equipment so that frame to frame analysis of performance can be made.

The measurement should be done with, and without, the aid so that comparison of performance can be made. In the case of the SOS, performances can be compared to that of similar type, such as the BSA. Such a comparison would require the use of a large number of blind people so that matching groups of subjects can be selected. Furthermore, performances should be monitored for a prolonged period after training so that the effect of learning can be determined. Of course, care should be exerted in deciding how much improvement in performance post-training is due to the aid and how much is just due to travel experience.

It should be noted that, even if the above measurement can be made, it only describes the level of proficiency of a subject's motor skill, or the ability to translate the sensory information into effective movement, but it does not indicate the degree of spatial perception obtainable through the aid. There is a quite different level of spatial perception between, say, the

BSA and the Long Cane, that is not obvious through the observation of only the motor performance. Describing the travelled routes can be an effective means of measuring the levels of spatial perception. However, constructing a score for each route to objectively and correctly measure the spatial perception is an involved task requiring special care so that the obtained results can be meaningful.

7.5 ON THE USEFULNESS OF THE SINGLE OBJECT SENSOR AS A MOBILITY AID

It can be seen that an evaluation program would involve a large number of blind people (at least 50, Nye, 1971) and would be over a prolonged period of time. The acute lack of suitable subjects within the reach of the university, the time, and the cost involved make a large and meaningful evaluation program outside the scope of this thesis. Nevertheless, it is thought that some indication of the potential usefulness of the SOS would be valuable to serve as a first step toward understanding the use of the device as a mobility aid. To this end, the following 2 stages procedure was adopted:

In the first stage, the mobility activities are analysed. The analysis was based on the check list advocated by Leonard and Wycherley and later refined and used in the evaluation of the BSA and the Laser Cane. In the analysis, the mobility activities are organised into a series of 5 progressive mobility levels such that a skill at a higher level is the result from a build-up of skills at lower levels. The level ranges from Perceptual Judgements to Complex Travel Skills. They are described in details in Section 7.5.1.

In the second stage, the potential usefulness of the SOS in helping a Long Cane user in these activities is estimated together with the possible rationales (Section 7.5.2). This was based on the author's experience with the aid, his observation of the limited exposure of the aid to blind users as well as the opinions expressed by a small number of users and mobility teachers. It is not an assessment of the usefulness of the aid but rather an informed opinion and therefore does not constitute a real evaluation. Again it is hoped that, in views of the difficulties involved in a meaningful evaluation program, the expressed opinions are useful in bridging the knowledge gap between the present state of the aid and future evaluations.

7.5.1 An analysis of mobility activities

A range of mobility sub-skills involved in a typical journey can be seen by considering the case of a blind pedestrian walking from his home to a grocery shop in the next block. From Fig. 7.5 it is seen that apart from having a cognitive map of the desired route (i.e., turn right outside his house and across the street once), some of the sub-skills that a blind pedestrian may need are:

(i) assessing his distance to the lamp post outside his house

(ii) avoiding branches of a tree along the foot path

(iii) following the path along the fences

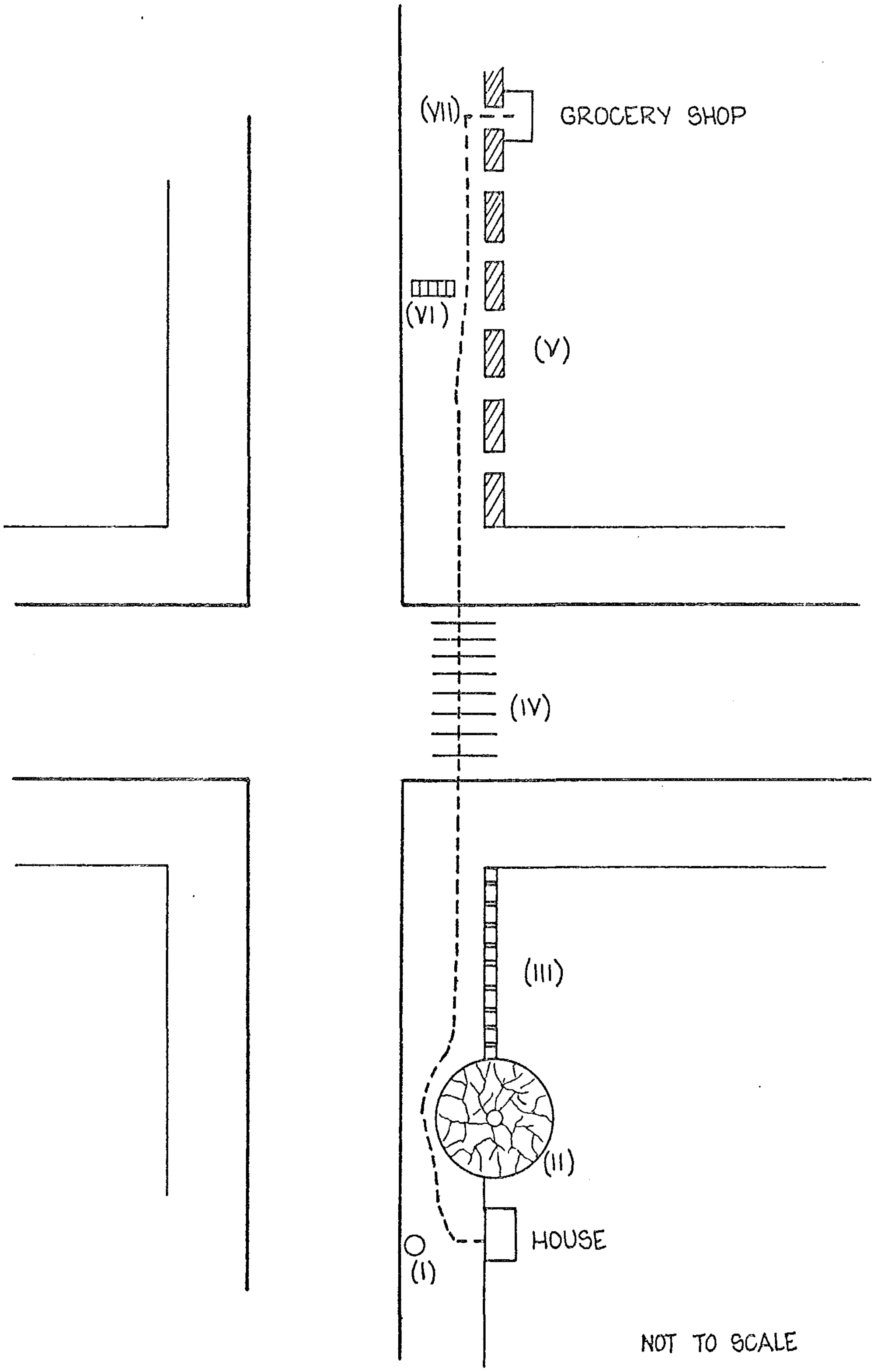
(iv) crossing a street

(v) following the path along the store fronts

(vi) locating a bicycle rack (2 shops before the grocery shop).

(vii) finding the doorway to the grocery shop

Some of the skills involved in the walk are peculiar for this type of environment. For example, following the path along the store fronts is a skill often used in a shopping centre but



A HYPOTHETICAL JOURNEY OF A BLIND PERSON TO A GROCERY SHOP IN THE NEXT BLOCK

SOME OF THE FEATURES OF THE ROUTE WERE

(I) LAMP POST OUTSIDE THE BLIND PERSON'S HOUSE
(II) OVERHANGING BRANCHES OF A TREE
(III) FENCES ALONG THE FOOTPATH
(IV) A STREET CROSSING
(V) STORE FRONTS ALONG THE FOOTPATH
(VI) BICYCLE RACK
(VII) GROCERY SHOP

FIG. 7.5

rarely used in a rural area. However, there are other basic skills that are often used in almost all types of environment, for example, assessing the distance of a stationary object (the lamp post), locating a landmark (the bicycle rack).

In general, the most basic skills involve the ability of a user to perceive the spatial information, such as assessing the distance and direction of stationary and moving objects. They are called here, the Perceptual Judgements (Table 7.2).

The next level of skill concerns the capability to translate the judgement into basic motor skills. They are called Perceptual Motor Skill and include approaching, avoiding objects as well as the ability to follow well defined path (i.e., paths with detectable boundaries such as fence, store front).

A typical walk may also involve some special task such as finding a doorway, taking one's place in a line. These tasks require not only an accurate perception of the position of the objects, but also a good mobility strategy. They are categorized as Special Detection and Motor Skills and are tabulated in table 7.3

The skills in the above categories, together with the orientation capability, form a repertoire upon which Complex Travel Skills are based. The latter (table 7.4) represent the ability of a user to move about in different types of environment.

Table 7.2 Perceptual Judgements and Perceptual Motor Skills

Perceptual Judgements:

1. Assessing the direction to stationary objects.
2. Assessing the distance to stationary objects.
3. Assessing the distance to moving objects.
4. Locating landmarks.

Perceptual Motor Skills:

5. Approaching stationary objects.
6. Avoiding low level obstacles (e.g., rubbish bin)
7. Avoiding normal height obstacles (e.g., lamp post).
8. Avoiding overhanging obstacles (e.g., branches of a tree).
9. Avoiding pedestrian in a crowded area.
10. Following path with hedgerows (fences).
11. Following path along store front.
12. Following path in hallways.
13. Following side walks bordered by grass.

Table 7.3 Special Detection and Mobility Skills

Special Detection Skills:

14. Finding a doorway.
15. Finding a gap between parked cars.
16. Finding up curb.
17. Locating a seat in a restaurant.
18. Locating a Clerk in a store.
19. Seeking pedestrian assistance.

Special Mobility Skills:

20. Crossing a street in a downtown area.
21. Squaring off to face objects and people.
22. Taking one place in a line.
23. Following pedestrians in order to cross a street.

Table 7.4 Complex Travel Skills

24. Travelling in moderate pedestrian traffic.
25. Finding a specific store downtown.
26. Finding one's way in familiar suburban areas.
27. Finding one's way in unfamiliar suburban areas.
28. Finding one's way in familiar shopping centres.
29. Finding one's way in unfamiliar shopping centres.
30. Finding one's way in familiar rural areas.
31. Finding one's way in unfamiliar rural areas.
32. Finding one's way in large open spaces.

7.5.2 On the usefulness of the SOS in the real environment

In general, the simplicity of the display has impressed many mobility teachers visiting the Department (Kay, Bui, Brabyn and Strelow; 1977). A general strategy to use the aid in the real environment has been described in the above reference. In the following section, the capabilities of the aid in helping Long Cane users to attain various mobility skills are estimated. The summary of the estimation is presented in Table 7.5 In this Table, G stands for great assistance to a Long Cane user, M for moderate and S for small.

(i) Perceptual Judgements:

The direction and distance to a stationary object situated within the field of illumination of the aid can be reliably perceived by a user through the IAD and the pitch of the representing sound. Therefore, most perceptual judgement skills of a Long Cane user can be greatly improved by the use of the SOS. One possible exception is the ability to locate landmarks for which the device seems to have only a moderate impact.

This is possibly due to the limited capability of the aid in representing the features of the landmark rather than its inability to convey to a user the landmark position.

(ii) Perceptual Motor Skills

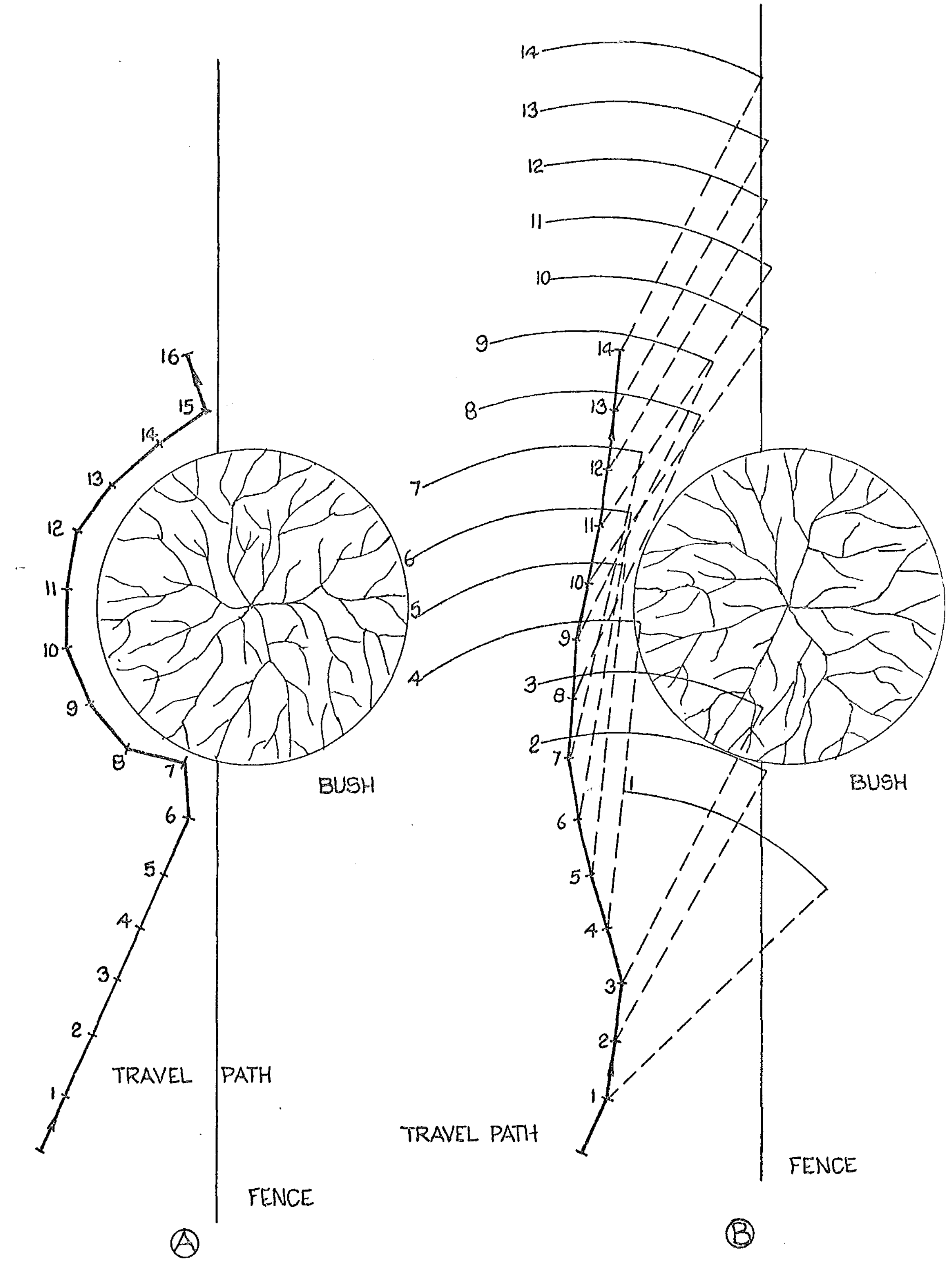
In this category, great improvement in mobility performance is possible in approaching, avoiding and shorelining with stationary obstacles of normal height. Where low level obstacles are concerned, only a moderate improvement is possible. Only a small improvement is expected in the tasks which involve moving obstacles. The reasons are briefly described below:

In approaching, avoiding and shorelining with normal height stationary obstacles, the path executed by a device user can be smoother than that of a Long Cane user, due to the longer range of the device, as shown in a hypothetical avoidance situation in Fig. 7.6. Finer control of movement is also possible due to the accuracy and reliability in the presented obstacle positions. Furthermore, advanced warning of the presence of an obstacle by the aid can reduce the psychological stress in the blind pedestrians, especially in the newly trained Long Cane users, who would anticipate possible collision with obstacles at the end of almost every step.

The aid offers lesser assistance in helping a blind pedestrian to avoid moving obstacles (mostly pedestrians) in a crowded area. However, it is still useful in minimizing cane contact with fellow pedestrians.

(iii) Special Detection and Special Mobility Skills

The aid only offers a small amount of assistance in helping the blind with the Special Detection tasks because of its



POSSIBLE PATHS PRODUCED IN AVOIDING A BUSH

Ⓐ USING A LONG CANE WITH THE CANE (AT MAXIMUM SWING OF ± 30°) JUST TOUCHING THE SHORELINING OBJECTS. (FENCES & BUSH)

Ⓑ USING A 5m RANGE 45° BEAM MOBILITY AID WITH THE EDGE OF THE BEAM JUST TOUCHING THE SHORELINING OBJECTS.

: TRAVEL PATH

ith : FIELD OF ILLUMINATING OF THE DEVICE AFTER THE ith STEP

FIG. 7.6

limited recognition capability. Moderate improvement is, however, possible in Special Mobility tasks. The skills involved in some of these tasks are briefly analysed below:

Finding a doorway is a rather complicated skill. Normally, from the auditory stimulus provided by the aid, a doorway may appear as an empty gap between two strongly reflected obstacles (the door frame). The extent of the empty gap depends on the width of the door and direction of movement. The detection, therefore, requires some attention to the flow of auditory signals, and may not be an easy task for newly trained device users.

Seeking pedestrian for assistance is a task in which a user can benefit from the aid. Although usually the presence of fellow pedestrians can be detected by the use of natural cues (such as the sound of footsteps) at a farther range than the maximum range of the device, the device provides reliable information about the position of a passing-by pedestrian. Therefore, the user can reliably know when to start inquiring.

The path produced in crossing a street can be refined because on the other side of the street can be detected half way across the street and used to correct any involuntary veering.

Taking one place in a line, such as joining a queue at a bus stop, can be simplified. A useful strategy is to shoreline with the line of people and to stop at the end of the line.

The device is moderately useful in the task of following pedestrians in order to cross a street. The long range of the aid allows a blind pedestrian to follow other pedestrians with minimum cane contact.

(iv) Complex Travel Skills

In general, the aid is likely to be of least impact in helping a blind in a crowded environment, mostly due to its inability to resolve closely spaced obstacles. In uncrowded environment, moderate to great help from the aid may be possible. The situations are analysed below:

In a crowded environment where many objects can be present in the illuminating field of the aid, it is not always possible to resolve them due to the characteristics of the binaural presentation. For example, if there are two objects of equal distance from the aid, the sound representing the objects will appear as coming from a single object situated somewhere between the two real objects. The objects can not be separated until movements of the user put one object outside the illuminating field of the aid.

The situation is actually more complicated. Because of the multiplicity of objects, a small movement of the user may induce the aid to "lock on" a new and nearer object, hence producing a sound of completely different IAD and pitch. Furthermore, another modification of IAD and pitch can also be introduced into the auditory stimulus due to the time and amplitude jittering effect, a characteristic of complex object. Thus the sound, at times, can appear to be "jumping" from one ear to another. The perception of the positions of objects in these situations has not been adequately studied. In any case, warning of collision is, however, still possible, although the task of re-establishing the travel course (after avoiding an object) may require additional spatial information from the environment.

In an uncrowded environment, the long range of the aid and its reliability in presenting the position of an object can be used to smoothly control locomotion. The capability of the aid in representing differently types of objects, although limited, can still be useful in locating some landmarks of a familiar route and in choosing landmarks to form a cognitive map for unfamiliar routes.

Table 7.5: Possible potential of the Single Object Sensor in helping the blind to attain various Mobility Skills

Section	No.	Mobility Skill	G	M	S
Section (i)	1.	Assessing the direction to stationary objects.	✓		
	2.	Assessing the distance to stationary objects.	✓		
	3.	Assessing distance to moving objects.		✓	
	4.	Locating landmarks		✓	
Section (ii)	5.	Approaching stationary objects.	✓		
	6.	Avoiding low level obstacles.		✓	
	7.	Avoiding normal height obstacles.	✓		
	8.	Avoiding overhanging obstacles.	✓		
	9.	Avoiding pedestrian in a crowded area.			✓
	10.	Following path with hedgerows.	✓		
	11.	Following path along store front.	✓		
	12.	Following path in hallways.	✓		
	13.	Following side walks bordered by grass.			✓
Section (iii)	14.	Finding a doorway.			✓
	15.	Finding a gap between parked cars.			✓
	16.	Finding up curb			✓
	17.	Locating a seat in a restaurant.			✓
	18.	Locating a Clerk in a store			✓
	19.	Seeking pedestrian for assistance.		✓	
	20.	Crossing a street in a downtown area.		✓	
	21.	Squaring off to face objects and people.	✓		
	22.	Taking one place in a line.		✓	
	23.	Following pedestrians in order to cross a street.		✓	
Section (iv)	24.	Travelling in a moderate pedestrian traffic.		✓	
	25.	Finding a specific store down-town		✓	
	26.	Finding one's way in familiar suburban areas.	✓		
	27.	Finding one's way in unfamiliar suburban areas.		✓	
	28.	Finding one's way in familiar shopping centres.			✓
	29.	Finding one's way in unfamiliar shopping centres.			✓
	30.	Finding one's way in familiar rural areas.		✓	
	31.	Finding one's way in unfamiliar rural areas.		✓	
	32.	Finding one's way in large open spaces.	✓		

7.5.3 Summary

In summary, the Single Object Sensor may be of moderate to great help to a Long Cane user in the perceptual tasks or in an uncrowded environment. In these situations, since the positions of objects can be sensed in advance and realiably determined, a path free of obstacles, characterized by a silent state of the aid, can be established so that the user can safely move.

The aid, however, may be of lesser help in a crowded environment where it is necessary to separate closely placed obstacles so that a clear path can be found. As mentioned earlier, the main reason is due to the low angular resolution of the aid, a characteristic of a wide beam, two receiving transducers system. Even so, the aid is still useful in minimizing collision and cane contact with obstacles and fellow pedestrians.

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CHAPTER 8

CONCLUSION

8.1 SUMMARY OF RESULTS

This thesis describes a feasibility study of a binaural single object sensor as a mobility aid for the blind. To facilitate spatial perception, it was argued that the aid should provide information about the nearest object only. and in a manner similar to natural auditory perception of space. Various portable experimental models of the SOS were designed and the mechanism of natural auditory localization was studied in an attempt to fulfil the above conditions. Spatial perception and control of locomotion with the display of the aids were also studied. The results can be broadly divided into 3 categories:

8.1.1 Localization and the transfer function of the pinna

The localization mechanism was theoretically and experimentally examined. It was found that the incidence of "in head" localization was markedly increased when the pinna was rendered ineffective; and when the pinna was pointed backward, 87% front-back reversion, in the reported sound direction, occurred. The results tended to substantiate the hypothesis that the pinna is the most important factor in producing the natural "out there" sensation.

An analogue cross-correlator was designed to determine the transfer function of the pinna. In the correlator, pseudo-random noise was used as the interogative signal, 4086 delay steps of 1 μsec each were provided. The bandwidth of the correlator was 100 kHz ±

3dB which corresponded to a spatial resolution in the cross correlation function of about 3.4mm.

The transfer function of the pinna was found to vary drastically with the direction of a sound source. In general, 3 main groups of reflectors on the pinna, the concha, the antihelix and the upper part of the helix, were identified. The sound reaching the ear drum, thus, consists of the direct sound and three groups of delayed replicas; the amplitude of which was also affected by the blocking of the sound by the tragus, the antitragus and the lobule. As a consequence, it was difficult to reproduce the modification process created by the pinna using straight forward electronic techniques suitable for a portable mobility aid.

8.1.2 Design of the Single Object Sensor

Initially, an experimental model of the SOS was produced using RTL logic and analogue circuitry. Although portable, it was rather bulky (Fig. 3.8) and consumed a considerable amount of power (200 mA at $\pm$ 15 V DC). Subsequent improved designs using CMOS logic to replace RTL and many of the analogue circuits, reduced the size, weight and power consumption of the aid down to a more acceptable level. At the present, a 5 hr continuous running is possible with a fully charged battery. The aid has a minimum number of internal adjustement and should therefore be suitable for commercial reproduction with very little modification.

In general, the aid consists of a spectacle frame and a small control box (11.5 cm x 9 cm x 2.5 cm). The former houses the oval transmitting transducer, two circular receiving transducers and its associated pre-amplifiers, and a pair of miniarturized earphones. The rest of the circuitry is contained in the controlled box, which is linked to the spectacle frame by an 8 strand cable.

Functionally, the aid detects only the nearest object in its illuminating field and presents the spatial information in form of a binaural train of 1 msec clicks, the rate of which is inversely proportional to the distance to an object. The direction to the object is determined by IAD with the lateralization constant being 0.5 dB/degree.

Other specifications of the aid are as follows:

Operating frequency: 80 kHz

Range: 2.5 m and 5 m

Beam Width: 45^{o} horizontal, $22^{o}5$ vertical.

8.1.3 Spatial perception and locomotion control with the SOS

In the control of locomotion in a laboratory, it was found that the magnitude of the lateralization cue or a small amount of training had a greater effect on the control of locomotion than any subjective difference between headphones and free-field listening conditions. Consequently, lateralization was used in the SOS as the mechanism for determining the direction to an object. Among the mechanism useable for lateralization (IAD, ITD and IAD in combination with ITD), IAD was found to be most suitable.

In the spatial perception field, studies of the pitch of the periodic pulses indicated that the pitch of the SOS auditory stimulus was inversely proportional to the distance to an object and, hence, varied in a similar manner as the pitch of reflected sounds observed in the natural echo-location phenomenon. The equal loudness contours of the periodic pulses were also determined to provide information for possible future use of loudness as an extra distance cue. In the process, it was found that the loudness was not solely determined by the number of excited critical bands and the intercomponent masking. The pleasantness of the sound was suggested as another contributing factor.

The aid was also found to provide a limited object recognition capability, due to the amplitude and time jittering effects in the audio pulses.

Further studies of the control of locomotion in a laboratory showed that the aid provided adequate spatial information for smooth locomotor control. Performances were found to be comparable with the Binaural Sensory Aid in a number of tasks ranging from shorelining to circumnavigating unknown shapes.

With regards to the use in the real environment, initial reaction from a limited number of mobility teachers introduced to the aid was encouraging. The simplicity of the display was much appreciated. However, due to the limited time and finance available, it was not possible to vigorously and properly evaluate its potential. As a substitue, suggestions as to its possible usefulness in a number of mobility activities were presented to serve as a basis for future evaluation.

8.2 SUGGESTED AREAS FOR FURTHER RESEARCH

The problem of interfacing a mobility aid to a human operator is a complex one, especially when the fundamental information about the requirement of mobility, and about the replacement of one sensory modality by another is not readily available. This thesis provides only some basic information about certain aspects of spatial perception by the SOS, many areas are not yet fully explored to further facilitate the spatial perception and, most importantly, to evaluate the potential usefulness of the device as a mobility aid. Some of these areas are briefly outlined below:

8.2.1 Evaluation of the Single Object Sensor

It is envisaged that the provided analysis of mobility can serve as a basis to determine the potential usefulness of an aid; a method of measurement, such as the once advocated by Armstrong as mentioned in Chapter 7, can then be used to provide an objective assessment of the performance of a user in these mobility activities. Also since base line data of acceptable mobility performance has not been established, an effective evaluation should be on a comparison basis, that is, the performance of the SOS is to be compared with that of Long Cane and other established mobility aids users.

8.2.2 Loudness as an extra cue for distance

It is conceivable that loudness can be used as an effective and natural extra distance cue. This question can be resolved in a controlled experiment where locomotion performances, with and without the loudness cue, can be compared. Naturally, the locomotion control task should be chosen so that the distance cue is fully utilized. In this respect, it is seen that the "approaching a target in a straight line" task as employed in Chapter 5 is unsuitable because the object direction, rather than the object distance, was the most important aspect. Of course, the task could be modified, such as stopping half way from various starting distances, to accentuate the use of the distance cue. Other suitable tasks include slalomming and circumnavigating unknown shapes.

8.2.3 A tonal auditory display

Subjectively, the auditory stimulus has been described by th mobility teachers exposed to the aid as providing sharper lateralized images than, say, the tonal display of the BSA. The reason being that clicks, with its wide frequency bandwidth, tend to be lateralized easier than tones. However, due to the "buzzing" characteristic of the repititious clicks, some found them to be somewhat unpleasant. The pleasantness should not have a great detrimental effect on the acceptance of the aid because, in normal use, the aid should be directed toward a clear path for most of the time and, thus, is totally quiet (until obstacles are encountered). Nevertheless, it may be advantageous to convert the clicks into a more pleasant stimulus. An experimental tonal display has been constructed, with the frequency of the auditory stimulus varied linearly with distance, being 200 Hz at 0.15 m and 3 kHz at 5 m. It was found to be more pleasant to listen to. The tonal generator used consists only of a ramp generator, a sample and hold circuit, and a VCO; and was not capable to reproduce the IAD necessary for lateralization. Modifications to the tonal generator are necessary (to sample the amplitudes of the echoes in the two channels and to modify the amplitudes of the produced tones accordingly) so that IAD can be preserved.

Excluding the topics directly related to the device, other areas are worthy of further investigation in their own rights. The most interesting one concerns the utilization of the sound modification effect of the pinnae in music reproduction:

8.2.4 Binaural recording and music reproduction

A lot of interest has been shown in the binaural, or dummy head, recording technique. Usually in these methods, a pair of microphones were placed at the ear drum position, or near the pinnae, to utlize the sound modification process created by the pinnae. Reproduced sound through headphones was found to produce a more "realistic" effect than conventional stereo recording. Commercial recordings include those produced by Senheiser, Binaural recording Corp. U.S.A., etc. The technique has been tried in the course of the project, using a pair of microphones placed at ear drum positions of an artificial head. Recorded sound was found to produce the "out there" sensation of natural listening condition. However, sounds appeared to come mostly from somewhere behind the listener; this front-back confusion is a well known problem with binaural recordings (Meares, 1974). It should be interesting to study the problem, especially when fine resolution of the pinna transfer function can be obtained (with the cross correlator mentioned in Chapter 5) to determine whether a likely small dissimilarity between the listener's pinnae and the recording pinnae is responsible for this front-back confusion.

Equally challenging is the problem of reproducing sound through speakers. Although various techniques have been advanced (for example see Kurer, Plenge and Wilkens, 1973) none seem to be completely successful.

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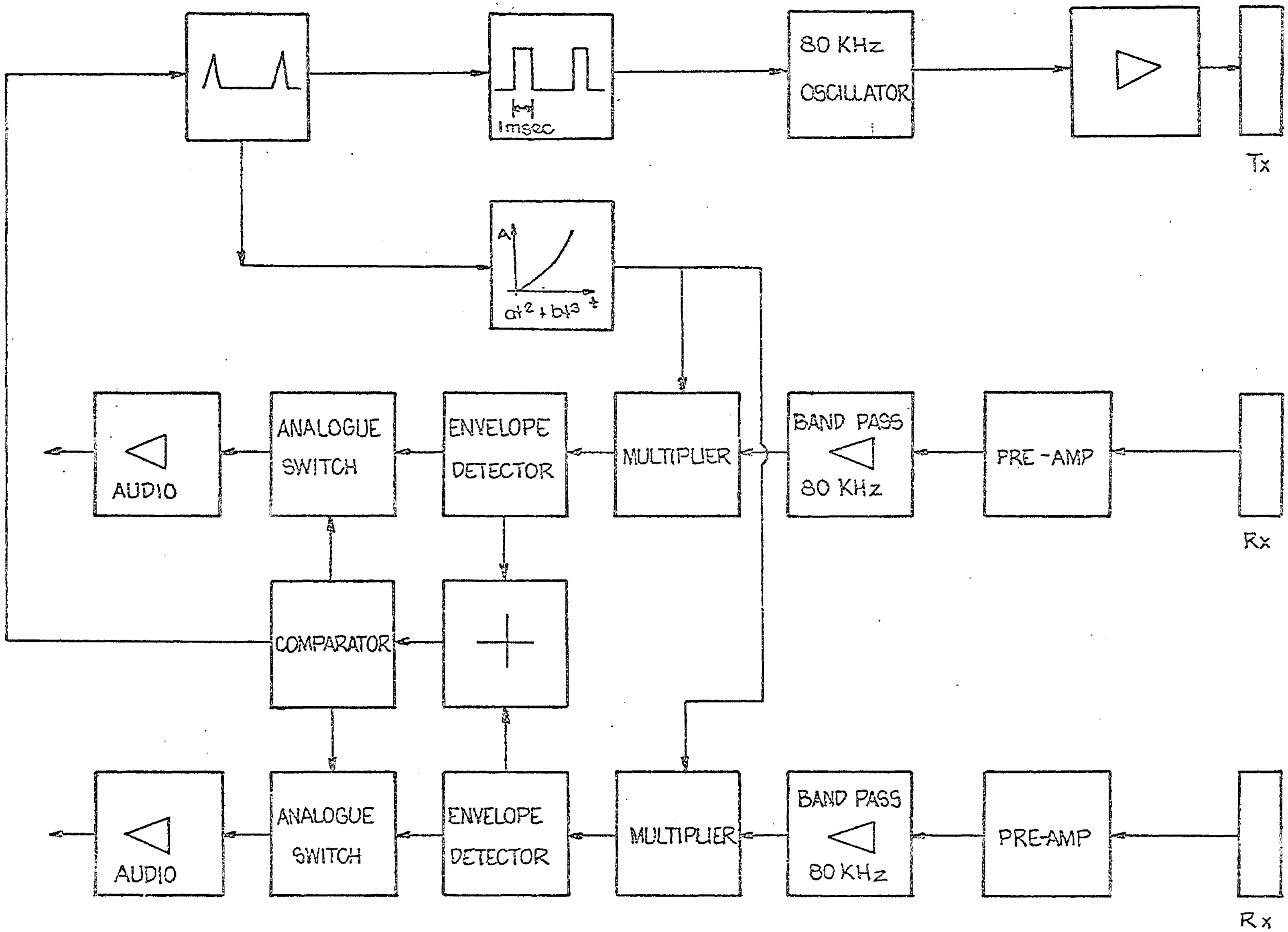
Appendix 1

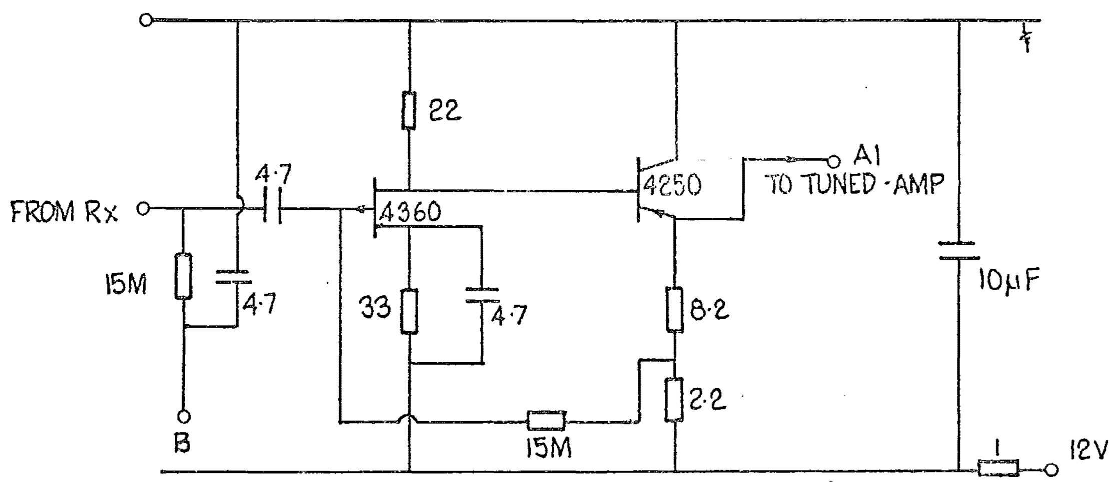
CIRCUIT DIAGRAMS OF AN EXPERIMENTAL MODEL OF THE SINGLE OBJECT SENSOR

The block diagram of the device is shown in Fig. 1.
Receiver pre-amp is shown in Fig. 2.
The Transmitter and time varying gain amplifier is shown in Fig. 3. The Receiver Audio Section is shown in Fig. 4.
All resistors values are in kΩ and all capacitor values are in KpF unless otherwise indicated.



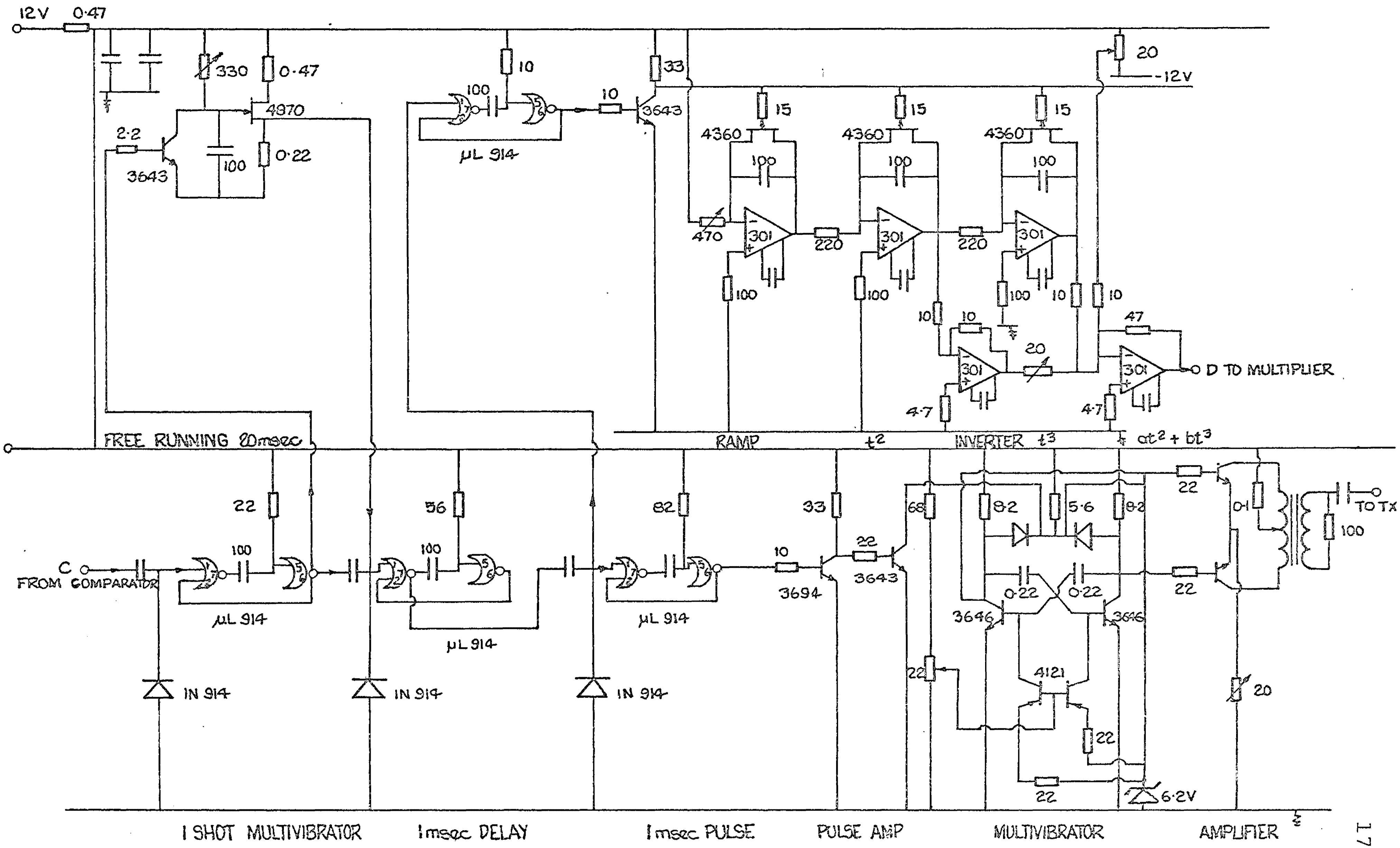
BLOCK DIAGRAMS OF AN EXPERIMENTAL MODEL OF THE SINGLE OBJECT SENSOR

FIG. 1



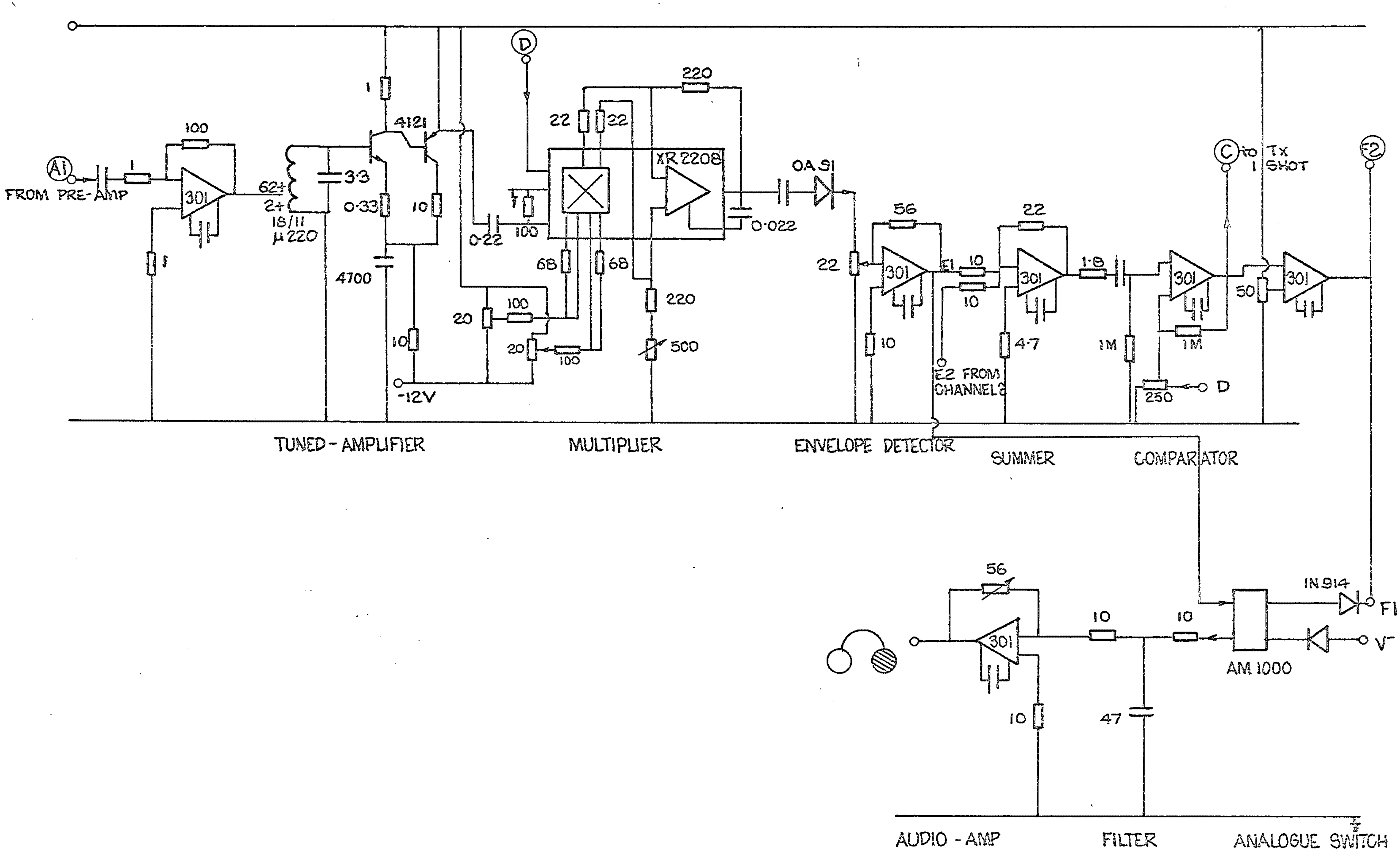
RECEIVER PRE - AMP

FIG. 2



TRANSMITTER & TIME-VARYING-GAIN AMPLIFIER

FIG 3



RECEIVER & AUDIO STAGE. 1 CHANNEL ONLY

FIG 4

APPENDIX 2

THE SONAR EQUATION

The intensity of the incident waves at the target distance D for an omnidirectional source is given by:

$$I_D = I_{ref} \left(\frac{Dref}{D}\right)^2 10^{-\alpha D/10} \text{ watts/m}^2$$

where I_{ref} = the intensity at the reference point

D_{ref} = the reference distance, taken as 1 m

α = attenuation constant

taking the directivity of the transducer into account, we have:

$$I_D = DF\ I_{ref} \left(\frac{1}{D}\right)^2 10^{-\alpha D/10}$$

where $DF = \frac{4\pi}{\Theta_H \times \Theta_V}$

$\Theta_H,\ \Theta_V$ = the horizontal and vertical beam width.

The reflected power from the target is given by

$$I_t = I_D \times \sigma \times R$$

where σ = the sonar cross section m^2

R = the target reflectivity measured in %

Assuming the target is an omnidirectional reflector, the intenstiy of the reflected echo at the receiver is:

$$I_r = I_{ref} \frac{\times \sigma \times R \times DF}{4\pi D^4} \times 10^{(-2\alpha D/10)}$$

Converting the intensity of sound pressure level, we have:

$$I_r = \frac{P_r^2}{\Psi oC} \; ; \quad I_{ref} = \frac{P_{ref}^2}{\Psi oC}$$

Hence $$P_r = P_{ref} \frac{1}{2D^2} \sqrt{\frac{\sigma \times R \times DF}{\pi}} \times 10^{(-\alpha D/10)} \; \mu \text{ bars}$$

If the receiver sensitivity is E_r dB with reference to 1V/ μ bar, then

$$e_r = P_r \, 10^{\,Er/20} \text{ volts}$$

At maximum range, the minimum detectable voltage is

$$e_r = S \text{ min volts}$$

Thus $$Smin = P_{ref} \frac{1}{2D^2} \sqrt{\frac{\sigma \times DF \times R}{\pi}} \times 10^{\,(-2\alpha D + Er)/20}$$

If the transmitter efficiency is E_t, then

$$e_t = P_{ref} 10^{\,Et/20} \text{ volts}$$

So $$Smin = e_t \frac{1}{2D^2} \sqrt{\frac{\sigma \times DF \times R}{\pi}} \times 10^{(-2\alpha D + Er - Et)/20}$$

Or $$\sigma = \frac{Smin^2 \times 4\pi \times D^4}{e_t^2 \times R \times DF} \times 10^{(2\alpha D - Er + Et)/20}$$

APPENDIX 3

THE FALSE ALARM PROBABILITY OF A GAUSSIAN INPUT NOISE

The probability density function of a Gaussian noise is given by*

$$P\ (v)\ dv = \frac{1}{\sqrt{2\pi\Psi o}}\ \exp\ \frac{-v^2}{2\Psi o}\ dv$$

where P (r): the probability of finding noise voltage between v and v + dv levels.

Ψo: mean square of the value of noise voltage.

The probability density of a band passed Gaussian noise is found to be:

$$P_{(R)}\, dR = \frac{R}{\Psi o}\ \exp\ \left(-\frac{R^2}{2\Psi o}\right) dR$$

where R: the amplitude of the band pass amplifier output.

A false alarm occurs when the noise voltage exceeds the threshold of detection level V_T. The probability of the false alarm is given by:

$$P_{fa} = \text{Probability}\ (V_T < R < \infty) = \int_{V_T}^{\infty} \frac{R}{\Psi o}\ \exp\ \left(-\frac{R^2}{2\Psi o}\right)\ dR$$

$$= \exp - \frac{V_T^2}{2\Psi o}$$

* SKOLNIK, M.I. Introduction to Radar Systems McGraw Hill 1962 Chapter 2.

The probability of a false alarm could also be considered as the ratio of the duration of the time the noise voltage exceed the threshold level, to the total time the receiver is operating

$$P_{fa} = \frac{\Sigma_{k=1}^{N} t_k}{\Sigma_{k=1}^{N} T_k} = \frac{<t_k>^{av}}{<T_k>^{av}}$$

where T_k: the time interval between the k^{th} and the $k + 1^{th}$ false alarms

$<T_k>$ av = T_{fa}: average false alarm time

t_k = the duration of the false alarm. For a band pass noise, the average duration of a noise pulse is the reciprocal of the band width B_{BP} of the band pass amplifier. Therefore $<t_k>$ av = $\frac{1}{B_{BP}}$

Thus we have $T_{fa} = \frac{<t_k>_{av}}{P_{fa}} = \frac{1}{B_{BP}} \exp \frac{V_T^2}{2\Psi o}$

The average time between false alarm T_{fa} for a 1800 Hz band pass Amplifier is plotted as a function of threshold to noise ratio in Fig. 1.

From Fig. 1 for the average time between false alarm to be in the region of minutes, the threshold to noise voltage has be be larger than 11 dB.

or $\frac{V_T}{\Psi o^{\frac{1}{2}}} = \geqslant 5$

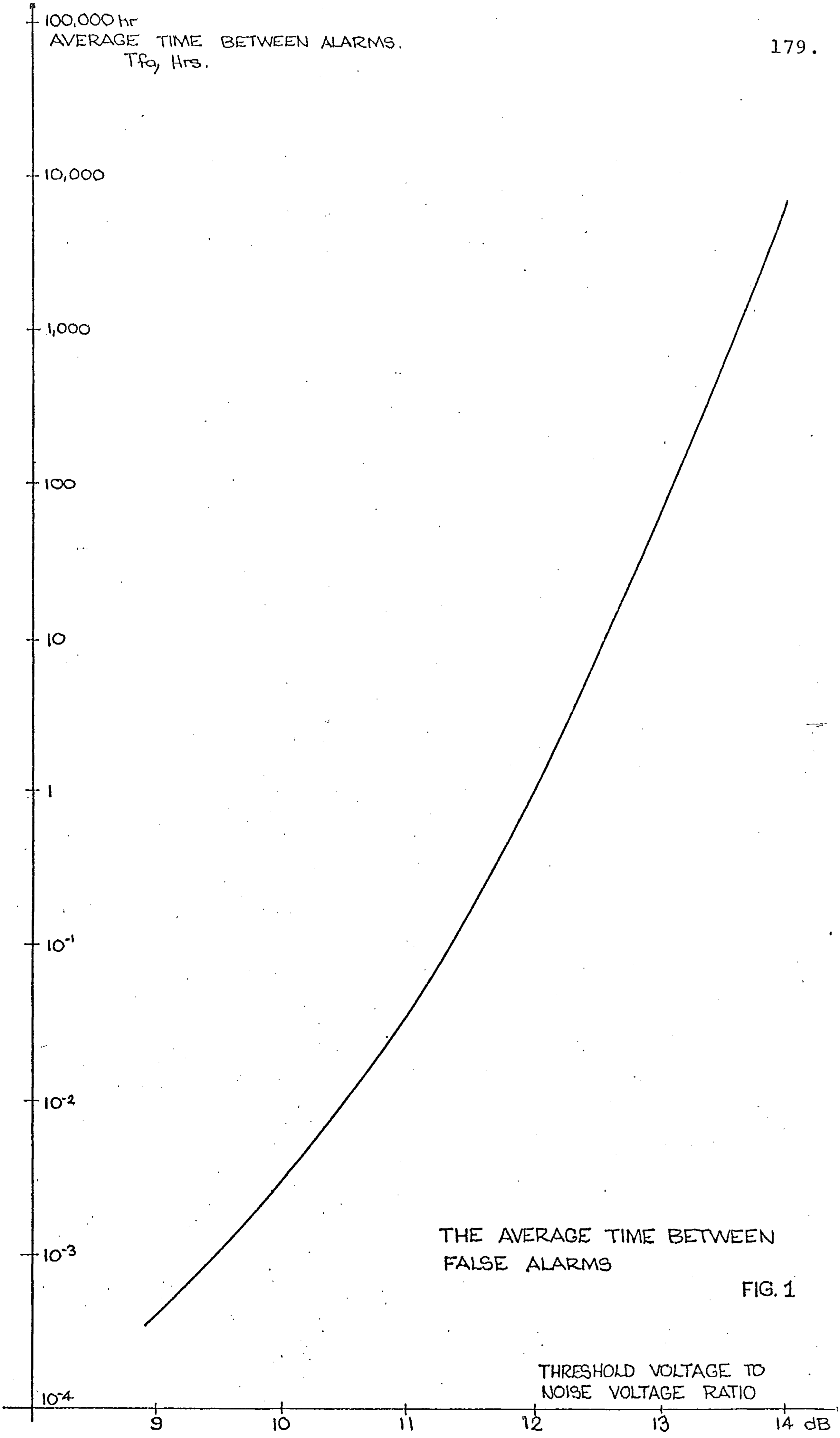

100,000 hr
AVERAGE TIME BETWEEN ALARMS.
Tfa, Hrs.
10,000
1,000
100
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
THE AVERAGE TIME BETWEEN FALSE ALARMS
THRESHOLD VOLTAGE TO NOISE VOLTAGE RATIO
9
10
11
12
13
14 dB

FIG. 1

APPENDIX 4

THE TRANSDUCER'S SENSITIVITY

The sensitivity of the transducer as transmitter and receiver was measured with the use of a Bruel x Kjaer 1/8" microphone.

At e_t = 10V RMS input to transmitter, the output voltage of the B&K microphone at 1 m away (Fig. 1) is V_m.

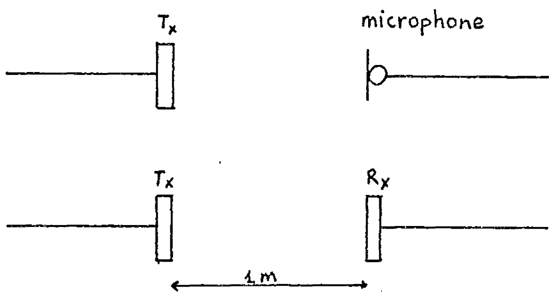


Fig. 1 Arrangement of transducers for sensitivity measurement.

V_m = -67.7 dB ref. 1 V_{RMS}

= 412 μV

The sensitivity of the microphone as specified by the manufacturer is

S_m = 40.7 μV/μ bar

Thus the Sound Pressure Level (SPL) of the sound field 1 m from the transmitter is:

P = 10.125 μ bar or 94 dB ref. 0.0002 μ bar

The transmitter sensitivity E_t is given by:

$$e_t = P_t \, 10^{E_t/20} \text{ volt}$$

this gives E_t = -0.1 dB ref. 1V/μ bar.

Replacing the B x K microphone by the receiving transducer and assuming that the sound field is unchanged, the output voltage of the receiving transduce is found to be:

$$e_r = 3548.1 \ \mu V$$

The sensitivity of the receiver E_r is given by:

$$e_r = Pr \, e^{Er/20}$$

with e_r = 3548.1 μV

and Pr = 10.125 μ bar,

we have E_r = -69.10 dB ref. 1V/μ bar.

Appendix 5

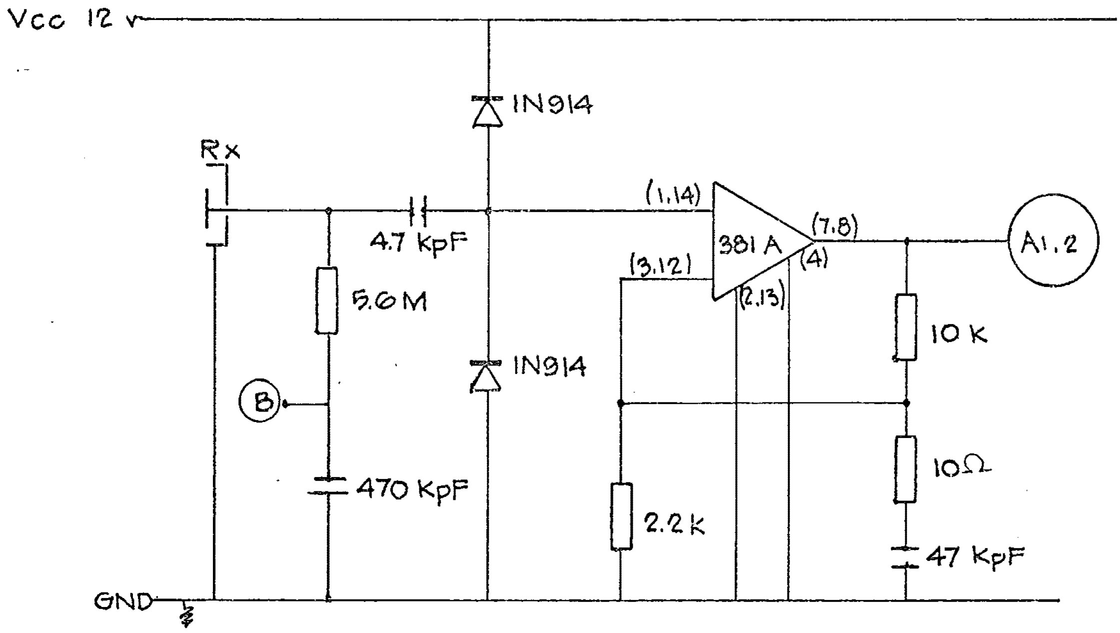
THE SINGLE OBJECT SENSOR CIRCUIT DIAGRAMS

The block diagram of the device is shown in Chapter 4. The pre-amp circuits diagram is shown in Fig. 1. The Band-pass amp is shown in Fig. 2 (one channel only).

The Audio Amplifiers of two channels and the signal detector circuits are shown in Fig. 3.

The Master Clock, the transmitting system and the Equal Level Control are shown in Fig. 4.

All resistors values are in ohms and all capacitors values are in pF unless otherwise indicated.



RECEIVER PRE-AMP

FIG. 1

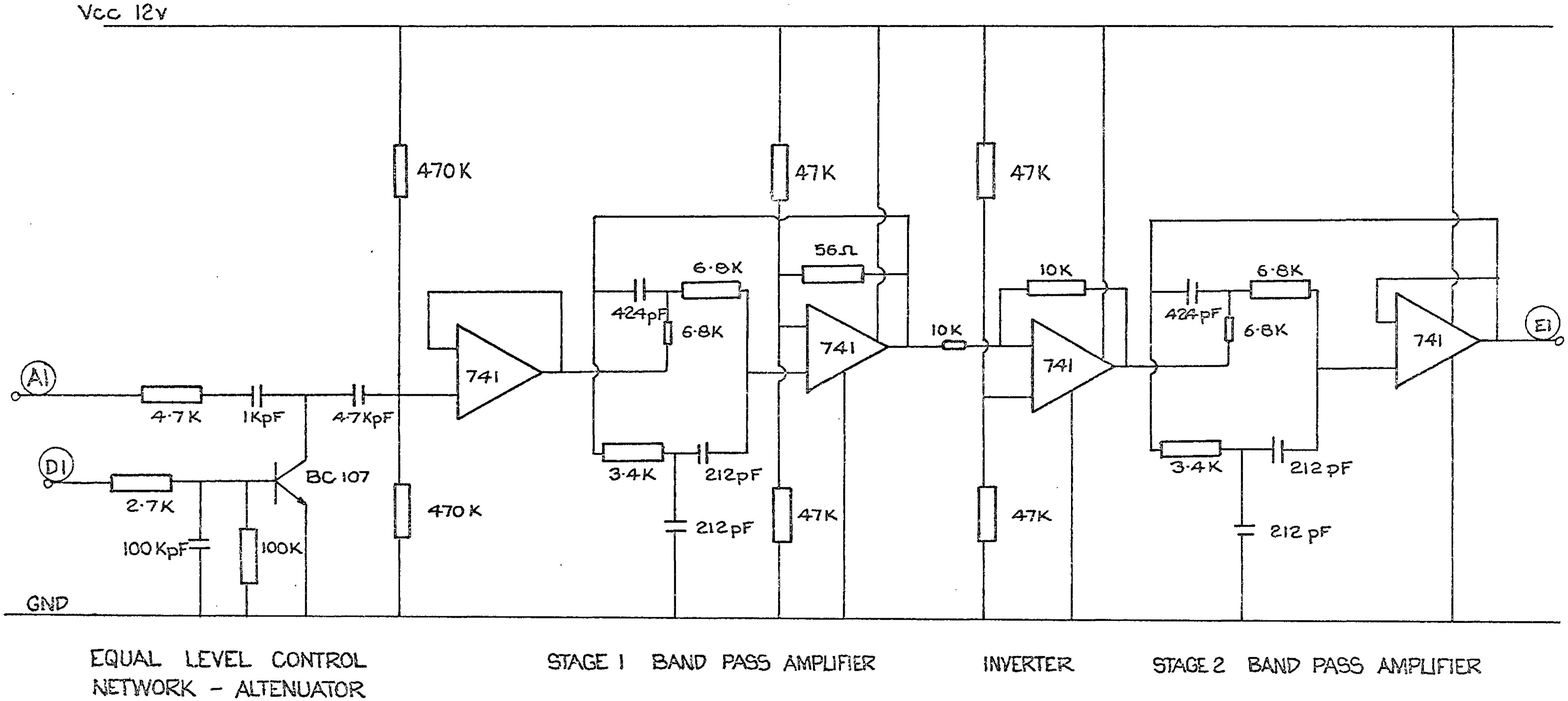
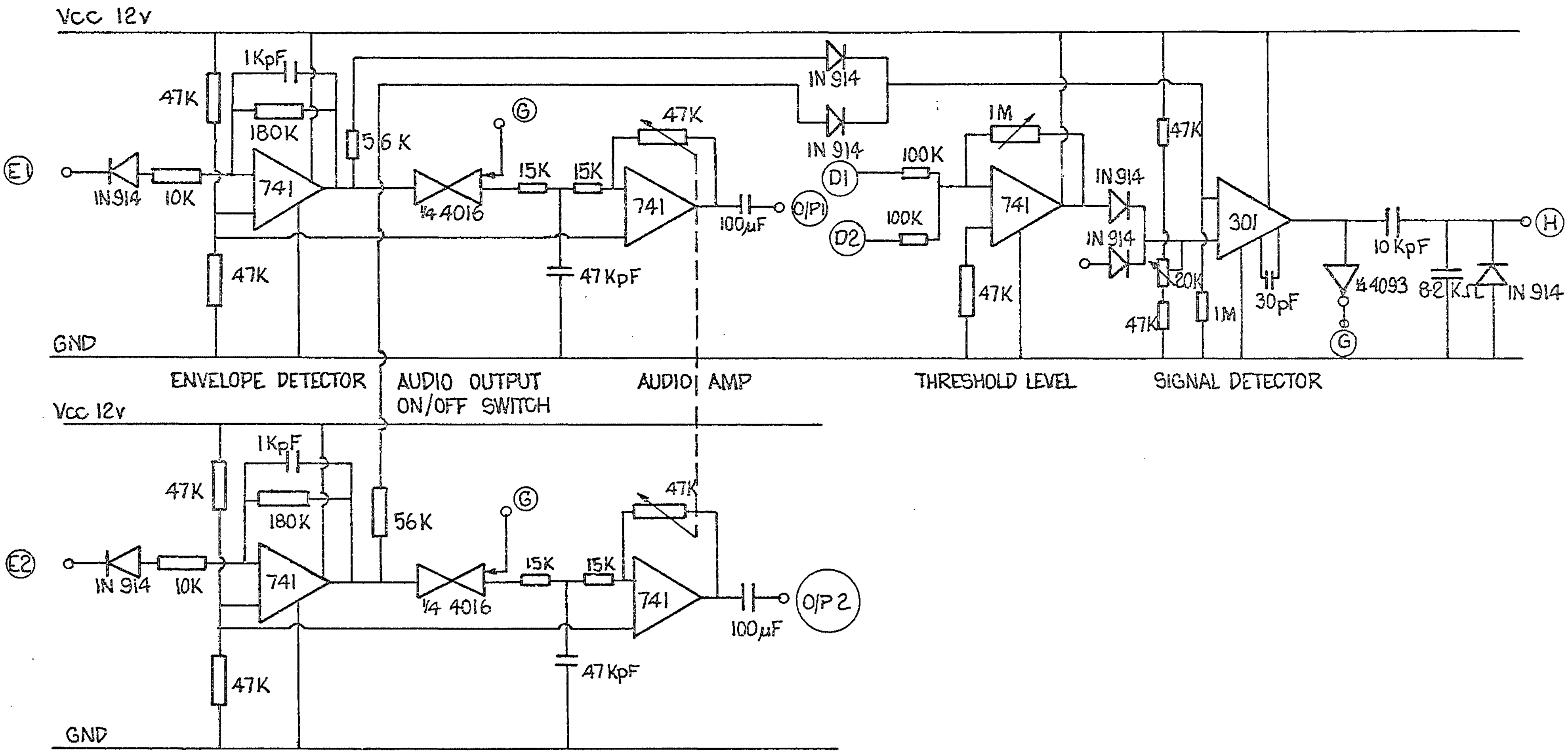
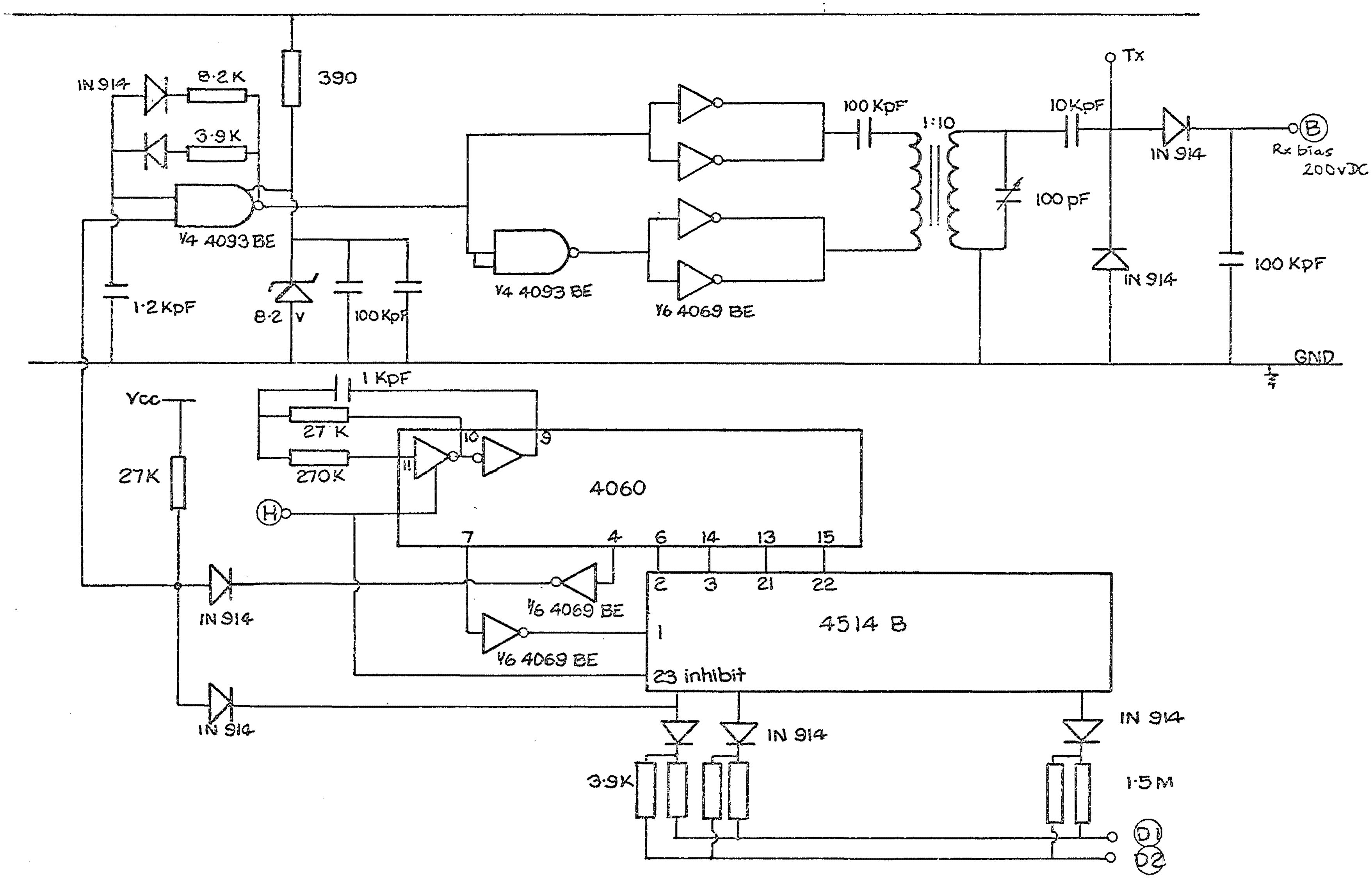


FIG.2 BAND PASS AMPLIFIER (1 CHANNEL ONLY)



THE AUDIO & CONTROL CIRCUITS

FIG.3



THE TRANSMITTING SYSTEM

FIG. 4

Appendix 6

DESCRIPTION OF THE CROSS CORRELATOR

The block diagram of the cross-correlator is shown in Fig. 1. Basically the cross correlator consists of five modules: the oscillator and divider module, the pseudo-random signal generators module, the start and integrator reset module, the automatic variable delay module, and the receiving module. The modules and the associated power supply was placed in a room adjacent to the anechoic chambers housing the transducer arrangements. The operation of the modules are briefly described below.

1. Oscillator and divider module (Fig. 2)

The timing of the cross correlator was controlled by a master oscillator and its associated divider circuits. The timing diagram is discussed in Section 6. The frequency of the master oscillator was set at 10 MHz. From this basic frequency, a divide-by-10 circuit was used to produce 1 MHz pulses to the automatic variable delay module (1 μsec increment, E output). Two independent divide-by-50 circuits were used to supply clocks pulses to the two PRSG (A and B outputs). A 5 Hz clock was also provided to restart the cycle. 5 Hz was chosen to allow sufficient time for the convolution integral at each particular ζ to complete.

2. Start and integrator reset module (Fig. 3)

The whole cross correlation process was started by applying a positive going pulse to the starting 1-shot multivibrator.

The starting pulse loaded 1 into the automatic variable delay module (F output), reset the integrator (D output) and started the 2nd PRSG (I output). From then on, the above cycle was automatically repeated every 200 msec.

3. Pseudo-random signal generators module

3.1 1st (delayed) PRSG (Fig. 6)

The PRSG was started by the output pulses from the automatic variable delay network (H input). Its output was then amplified by a wideband amplifier before applying to the transmitting transducer. A 10:1 step up transformer was also used to increase the peak output to 200 V p.p. The PRSG was automatically stopped, just before the pulses were repeated, by an end-of-burst detector. A pulse was then produced (J output) to reset the sample and hold circuit of the receiving module.

3.2 2nd (undelayed) PRSG (Fig. 4)

The PRSG was started by the output pulses of the variable 1-shot multivibrator in the start and integrator reset module (I input). Its output was amplified in the same manner as the 1st PRSG.

4. The automatic variable delay module (Fig. 5)

Upon pressing the start button, a load pulse was applied to the count-up counter. The counter was then incremented by one every 200 msec by the 5 Hz load pulse (D input) from the start and integrator reset module. When 4086 delay steps were completed, a reset pulse was sent to the start and integrator reset module (G output) to stop the whole process. The number of the delay steps could be visually observed by connecting a counter (Advance

Timer-Counter TC 11) to the H output. Meanwhile, every time the count-down counter reached 0, an output pulse was sent to the PRSG module (H output) to start the 1st (delayed) PRSG.

5. Receiving module (Fig. 7)

Outputs from the receiving transducers were amplified by low-noise amplifiers LM 382 and then wide-band amplifiers LM 318. The amplifiers were mounted closed to the transducers to reduce the amount of pick-up noise. The outputs were then multiplied, using a four-quad. multiplier XR 2208. The gain of the output op-amp of the multiplier was deliberately reduced to improve the multiplier bandwidth. The bandwidth of the amplifier-multiplier system was 200 kHz $\pm$ 3 dB. The output of the multiplier was integrated and then sampled by a combination of LM 308 op-amp and 3N 128 JFET. The samples were amplified and plotted using an X-Y plotter (Hewlett-Packard 7035 B X-Y Recorder) with a time base of 20 sec/cm (Hewlett-Packard time base type 170108 AM). This corresponded to a time base of 100 ζ/cm or 100 µsec/cm. Note that the pinna was mounted in front of the receiving transducer corresponding to the "delayed PRSG" transmitter.

6. Timing diagram

The timing diagram is shown in Fig. 8. Some timing characteristics are as follows:

No. of pulses in a burst:	$2^{15} - 1 = 32767$ pulses
Burst Length:	$\dfrac{32767}{200 \text{ kHz}} \simeq 160$ msec
Cycle Length:	$\dfrac{1}{5 \text{ Hz}} = 200$ msec

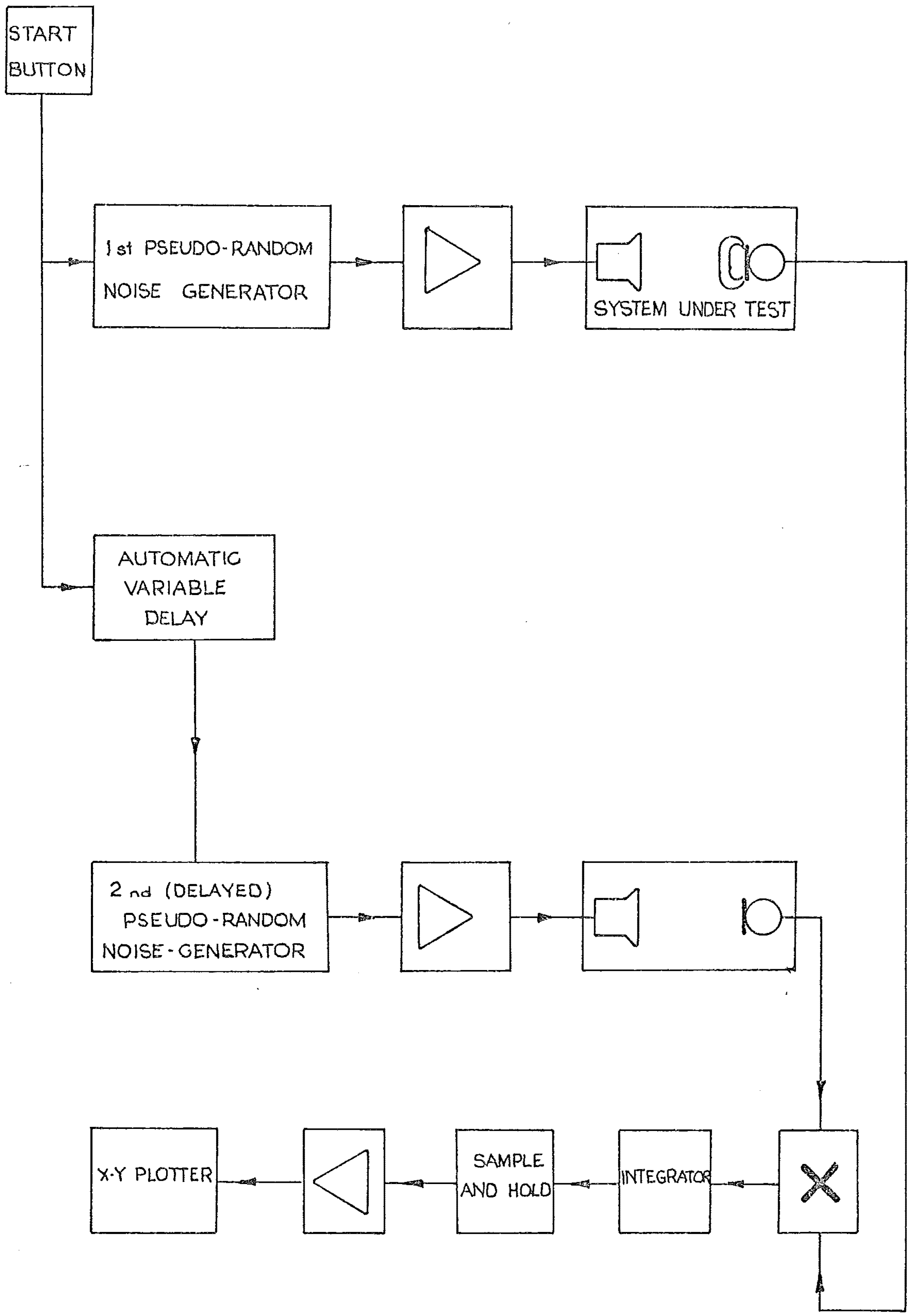
Max. delay: 2^{12} = 4096 pulses = 4096 μsec

Correlated distance: 1.4 m

A variable 1 shot multivibrator was introduced (Fig. 3) to vary the timing of the starting pulse for the undelayed PRSG. This was necessary to compensate for any variation in the transmitter - receiver distance of the two transducer arrangements. In the experiment, it was set between 0.4 and 1 msec. Note that since the pinna was mounted in the "delayed" transducer arrangement, the peaks at larger ζ, observed in the cross-correlation function $\Psi_{21}(\zeta)$, corresponded to shorter sound path, i.e., peaks at largest ζ corresponded to the direct sound and peaks at the smallest ζ corresponded to the farthest reflector on the pinna.

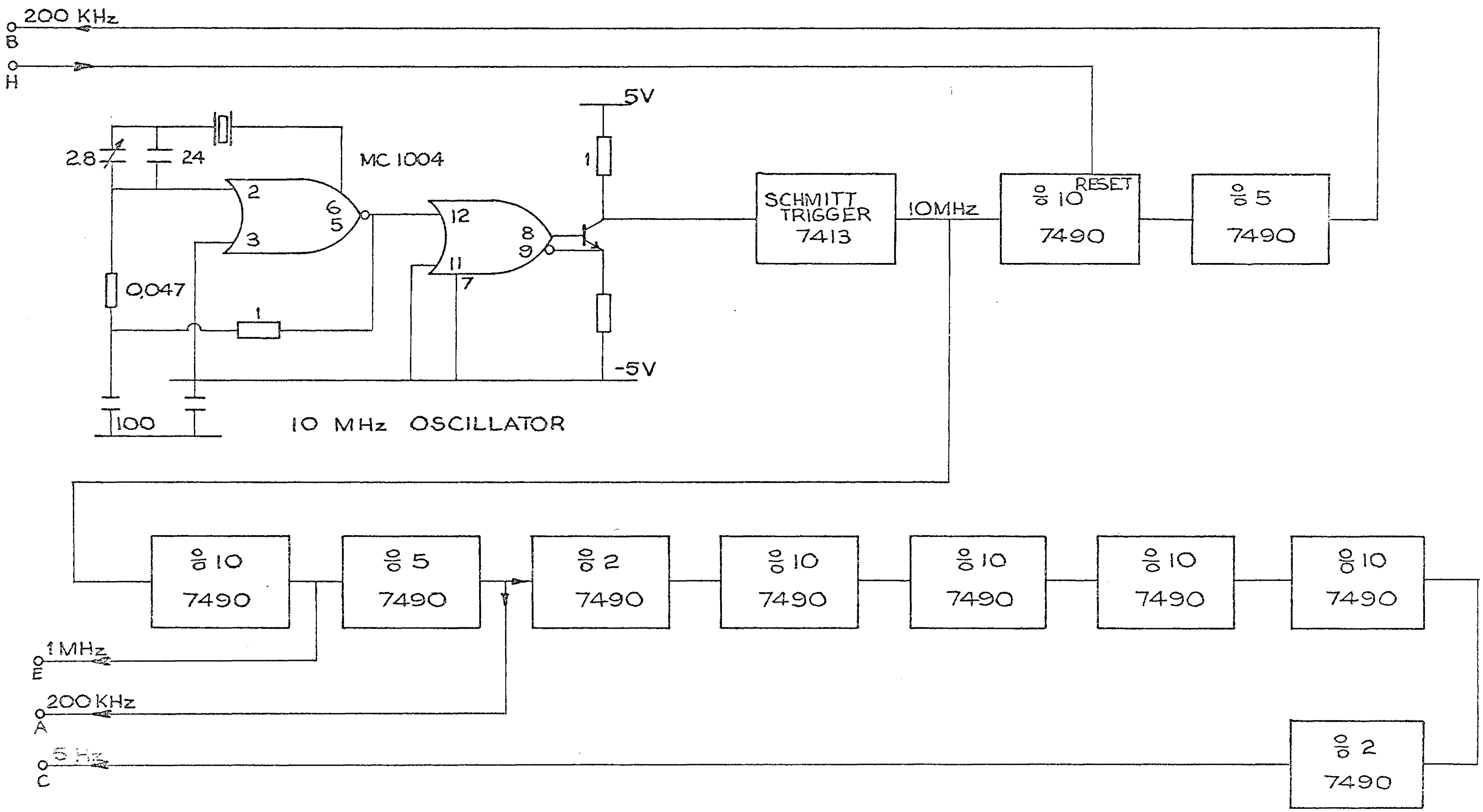
7. The Transducers

The transmitting and receiving transducers were of solid dielectric electrostatic type. They were circular and 75 mm in diameter. The frequency response of the transducers are shown in Fig. 9.



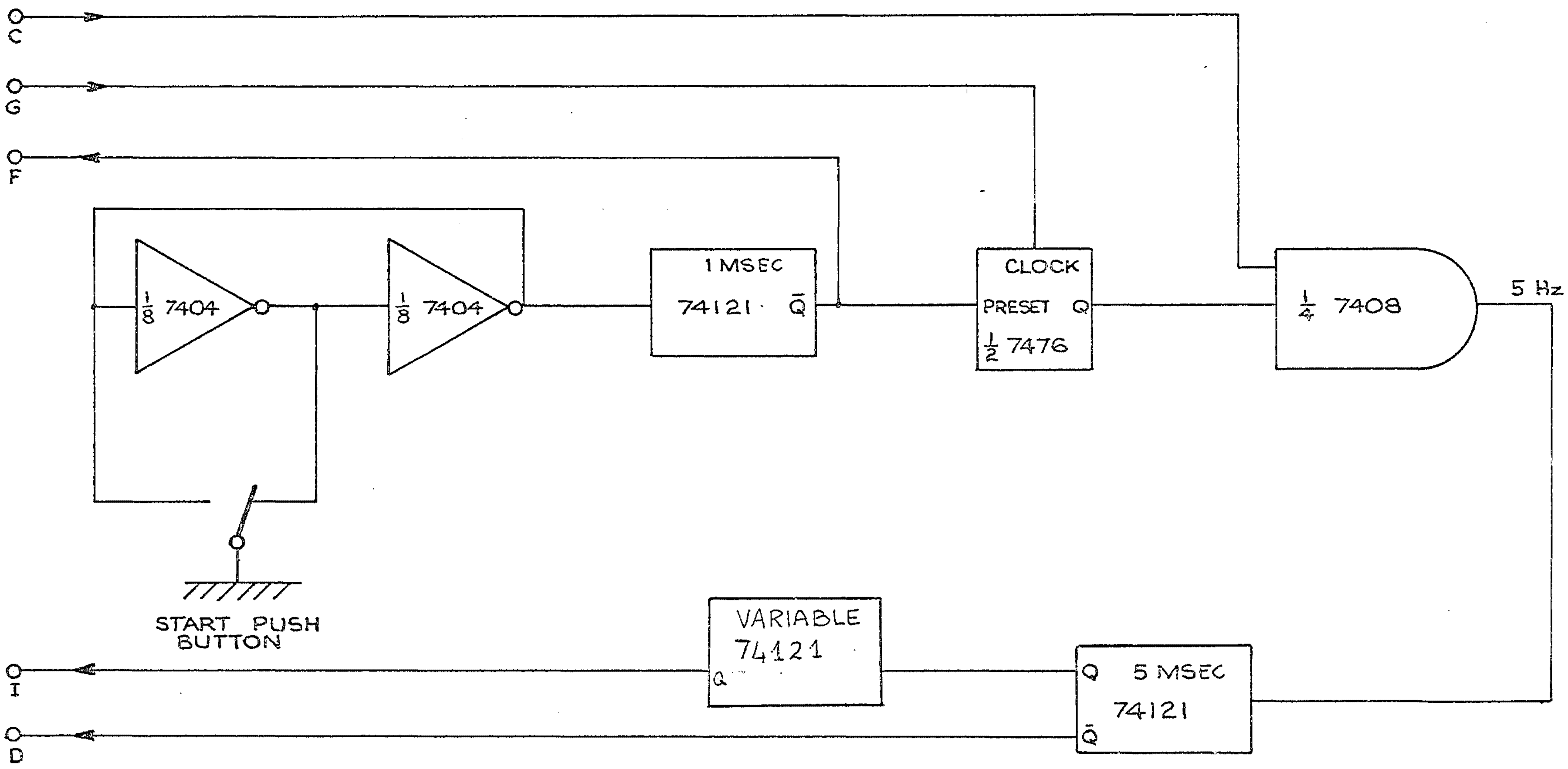
CROSS-CORRELATOR BLOCK DIAGRAM

FIG. 1



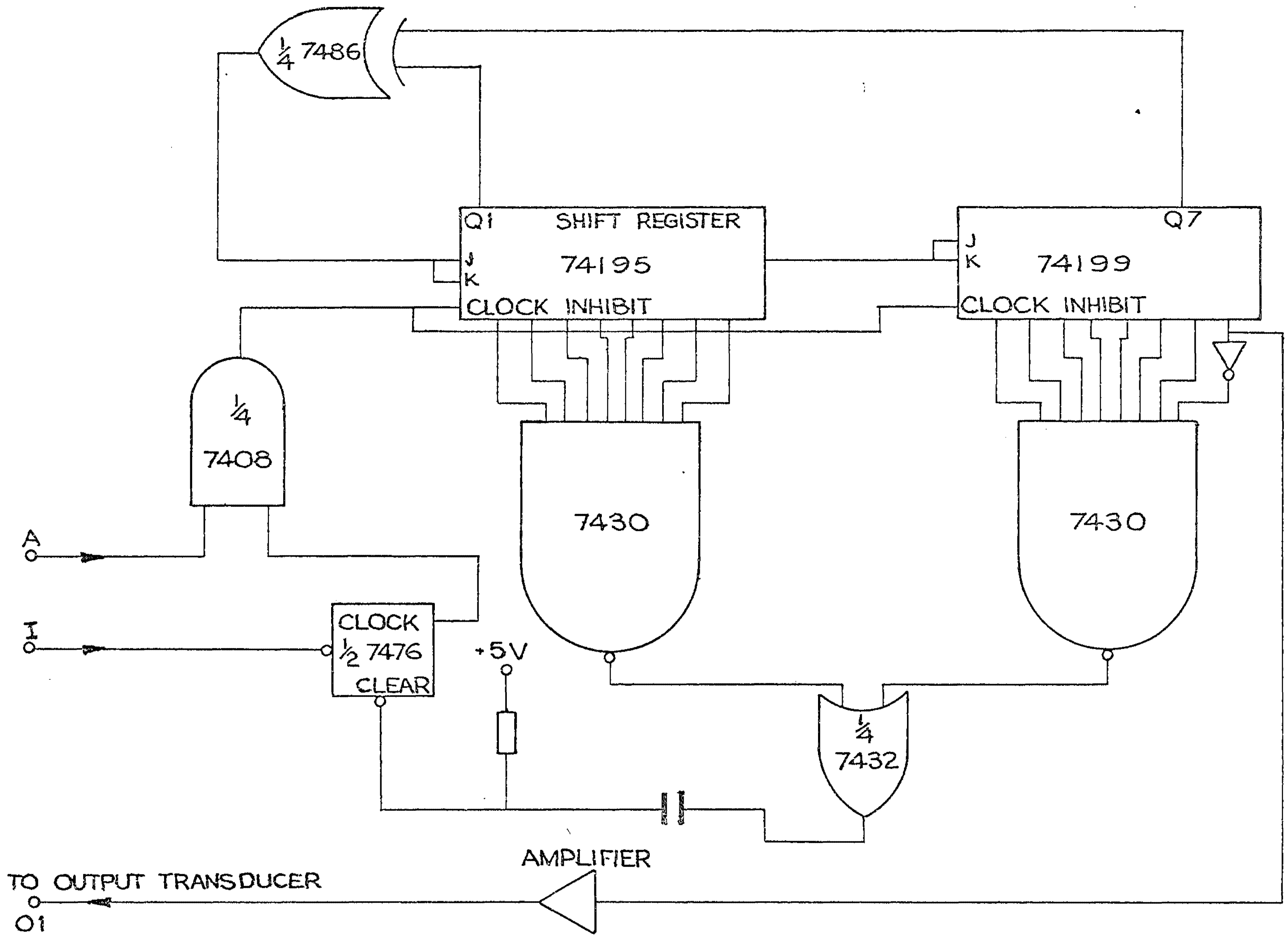
OSCILLATOR AND DIVIDER MODULE

FIG. 2



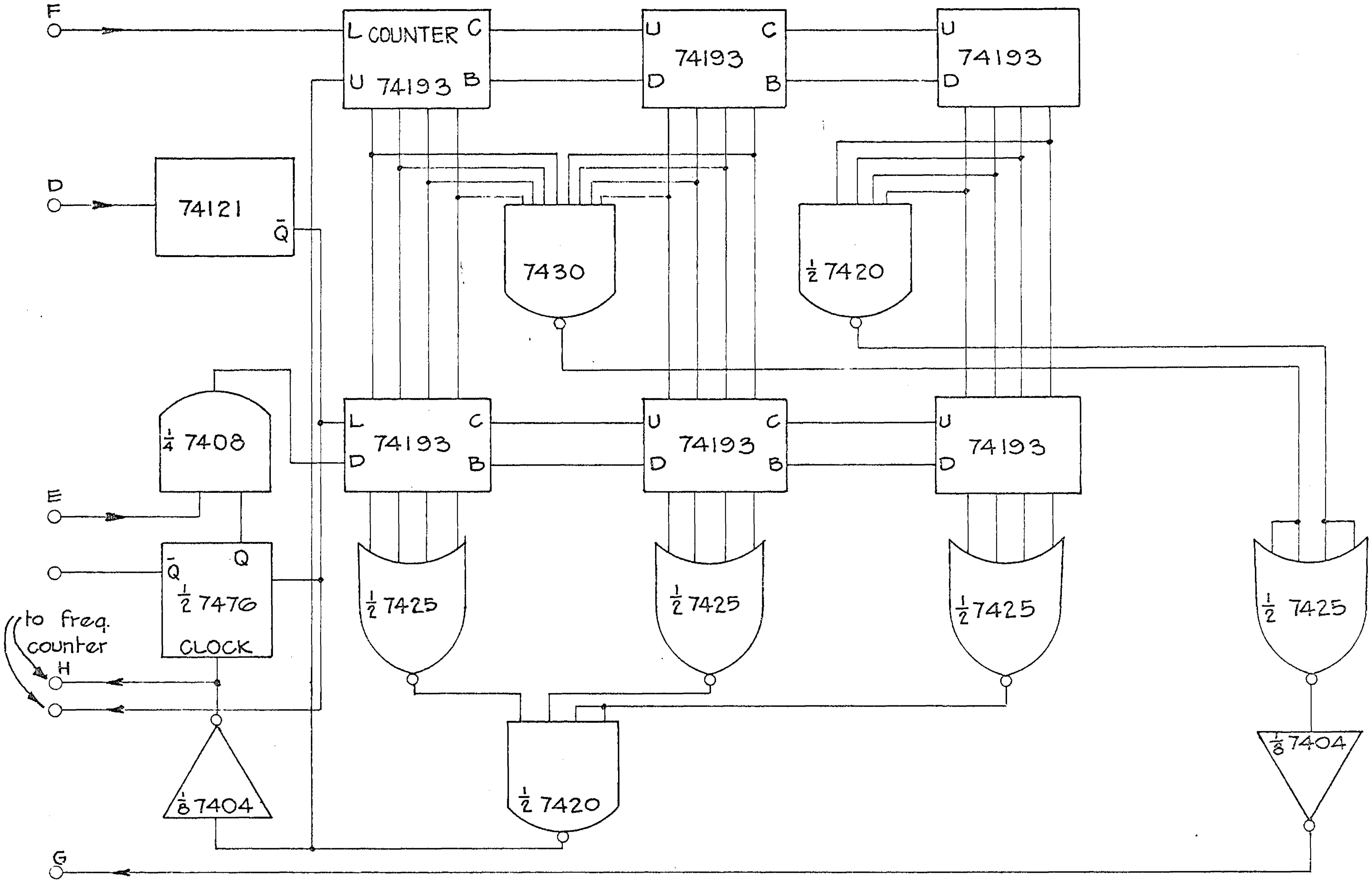
START AND INTEGRATOR RESET MODULE

FIG.3



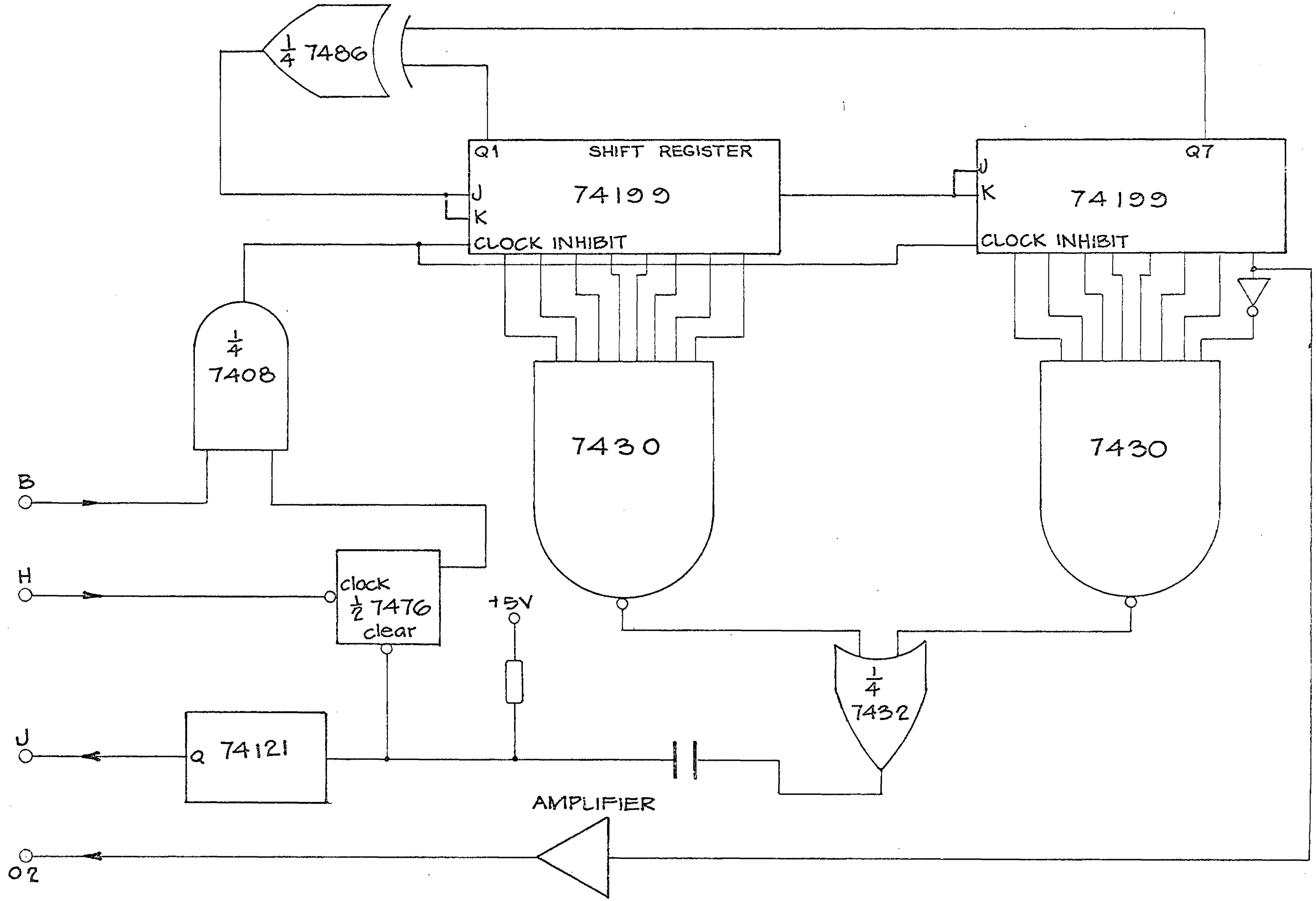
2nd PSEUDO RANDOM NOISE GENERATOR.

FIG. 4



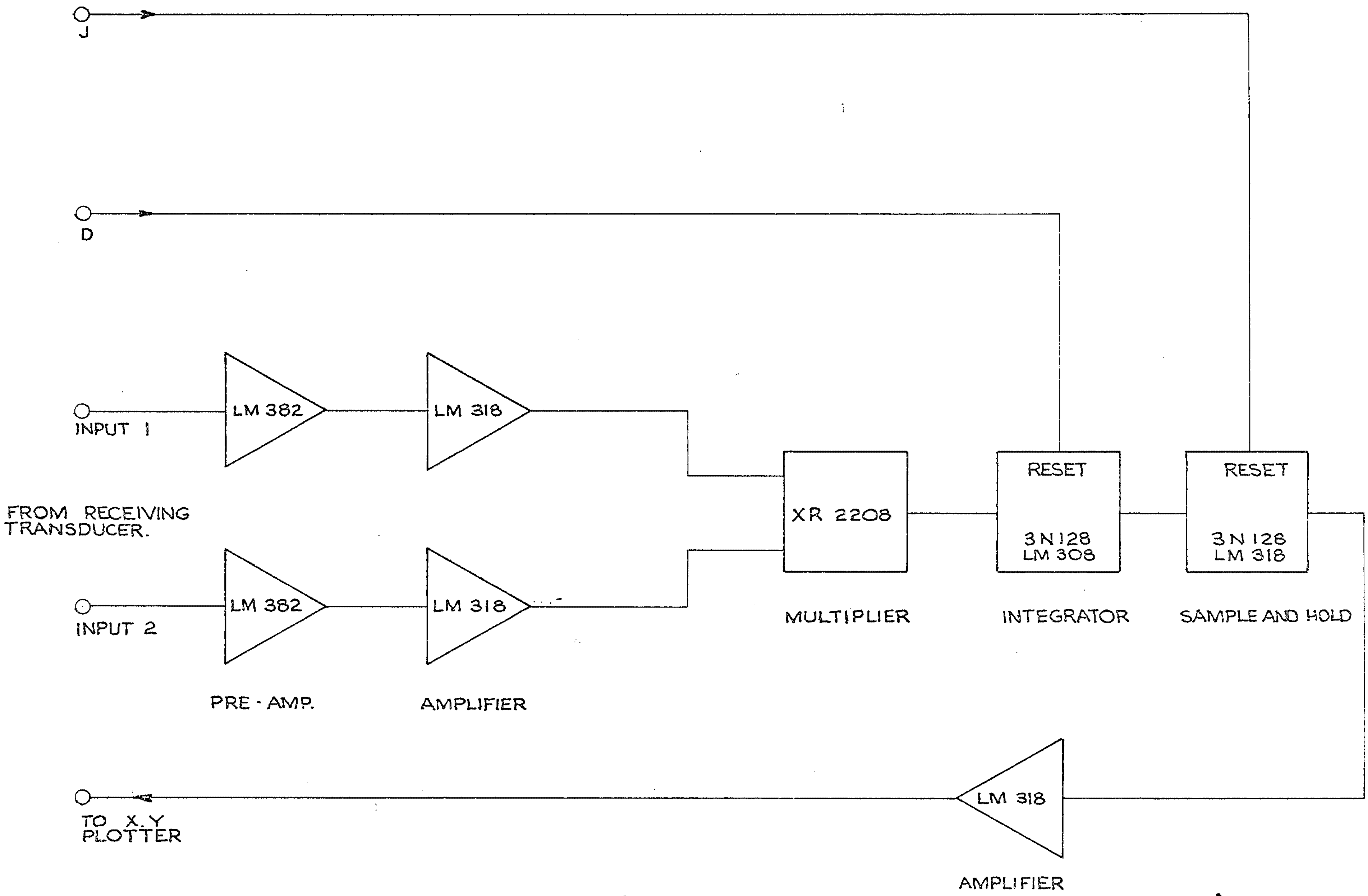
AUTOMATIC VARIABLE DELAY MODULE

FIG. 5



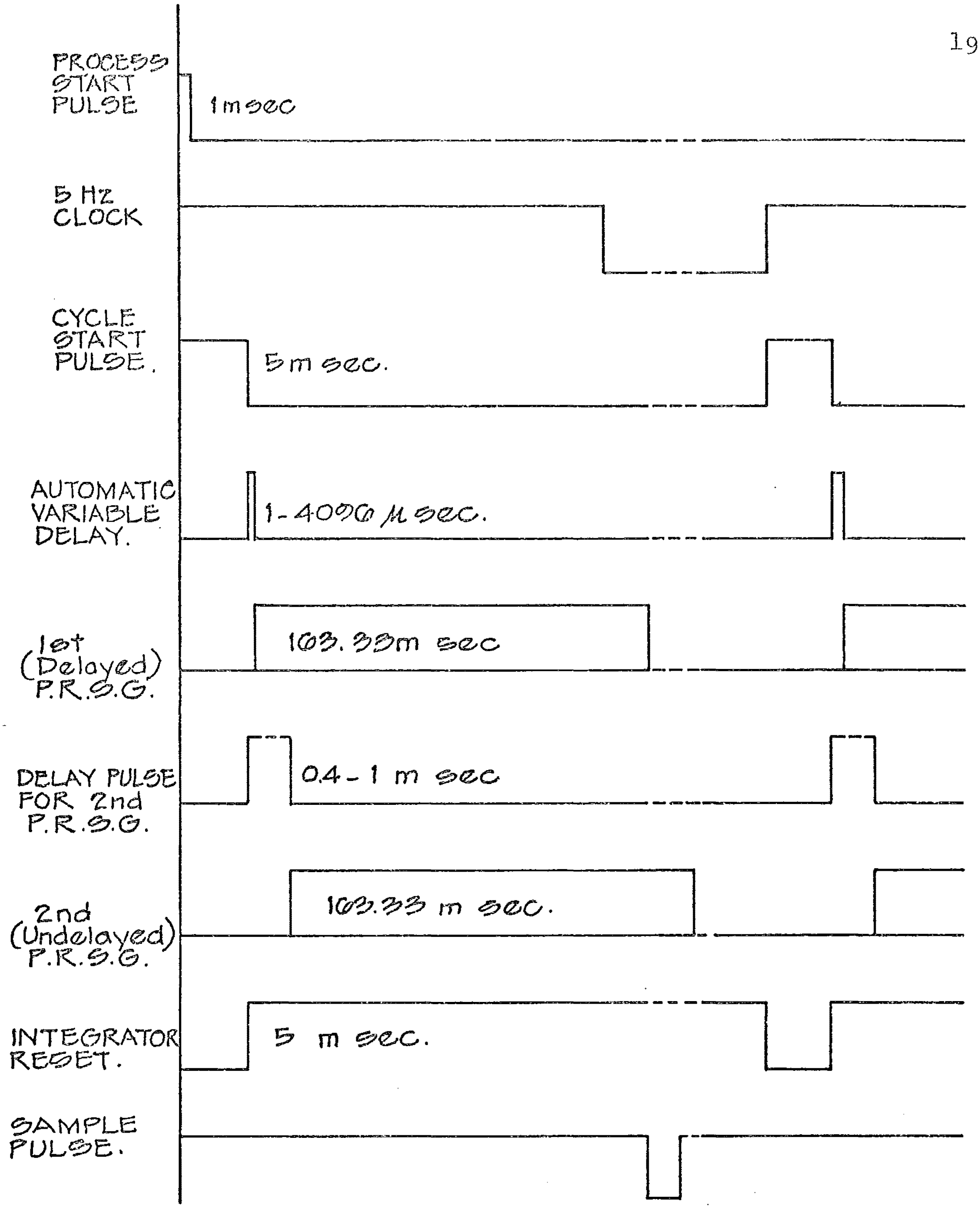
1st (DELAYED) PSEUDO RANDOM NOISE GENERATOR

FIG. 6



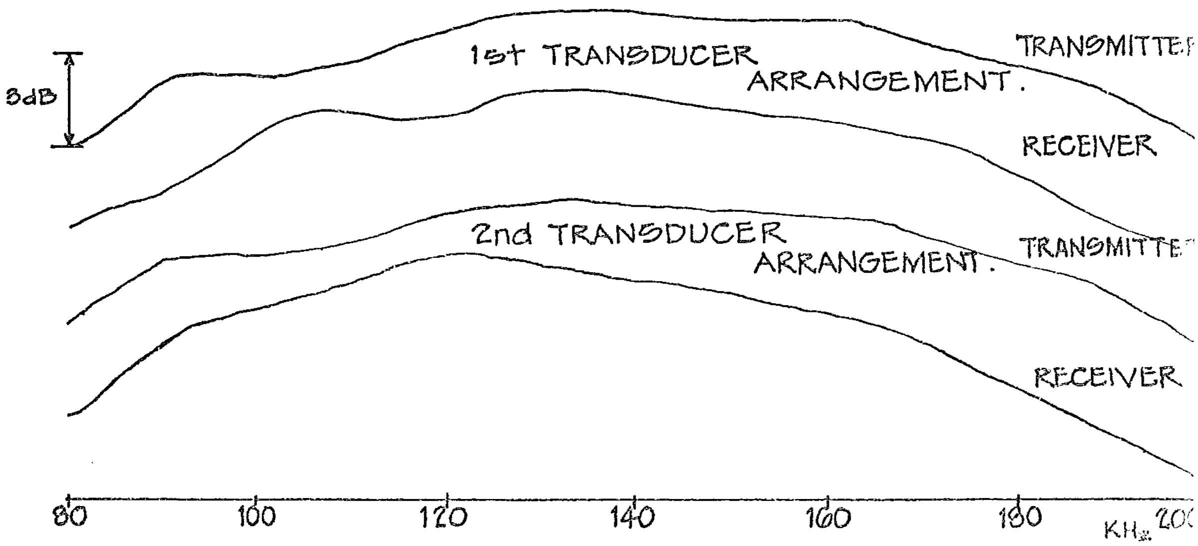
RECEIVING MODULE (MULTIPLIER AND INTEGRATOR)

FIG.7



CROSS-CORRELATOR TIMING DIAGRAM.

FIG. 8.



FREQUENCY RESPONSE OF THE TRANSMITTING & RECEIVING TRANSDUCERS.

FIG. 9.

APPENDIX 7

EFFECT OF PLEASANTNESS ON THE LOUDNESS OF PERIODIC PULSES

1. INTRODUCTION

The equal loudness contours of periodic pulses have been studied in Section 6.4. The shape of the contour in the middle range of the rates of repetition concerned was adequately explained in terms of the number of excited critical bands. However, there was an apparent increase in loudness at low and high rates of repetition that has not been sufficiently accounted for by the critical bands alone. Since subjects reported a general dislike for sounds at very low or very high rates of repetition, it has been argued that the pleasantness of the sound can also influence judgement on loudness.

In this experiment, the pleasantness of periodic pulses studied in Section 6.4 are evaluated to determine whether the pleasantness of the periodic pulses can supplement the critical band theory to explain the change of loudness with rates of repetition.

2. PROCEDURE

The pleasantness was evaluated by a numerical rating procedure, in which a reference train of periodic pulses (reference sound, 200pps) was assigned 100 marks, and subjects were asked to assign a mark for each test period pulses (test sounds). No upper nor lower limits were set for the mark of the test sounds. The SPL of the test sounds was designed to follow the subjective equal loudness contour, corresponding to the 60dB SPL of the reference sound, obtained in the loudness experiment. Each test sound was presented four times; the results were computed from the last two presentations. The test sounds, the reference sounds as well as the method of presentation and the apparatus were the same as in the loudness experiment. The 10 subjects participating in this experiment are those who participated in the loudness experiment.

3. Results

The mean marks given by the subjects ranged from 0 for the least pleasant sound to 162.5 for the most pleasant sound. The marks are ranked (Ferguson, 1971) and tabulated in Table 1.

A non-parametric test of significance showed that $X_v^2 = 49.8$ which was below the 0.001 level of significance. Thus, there was a significant difference in the ranks of the pleasantness at different rates of repetition. The difference can be seen in Fig. 1, showing the average rank of the periodic pulses as a function of the rates of repetition .

Discussion

Fig. 1 shows that the rank of the periodic pulses was at the lowest mark at the lowest rate of repetition. It improved as FR increased up to 400pps, then declined.

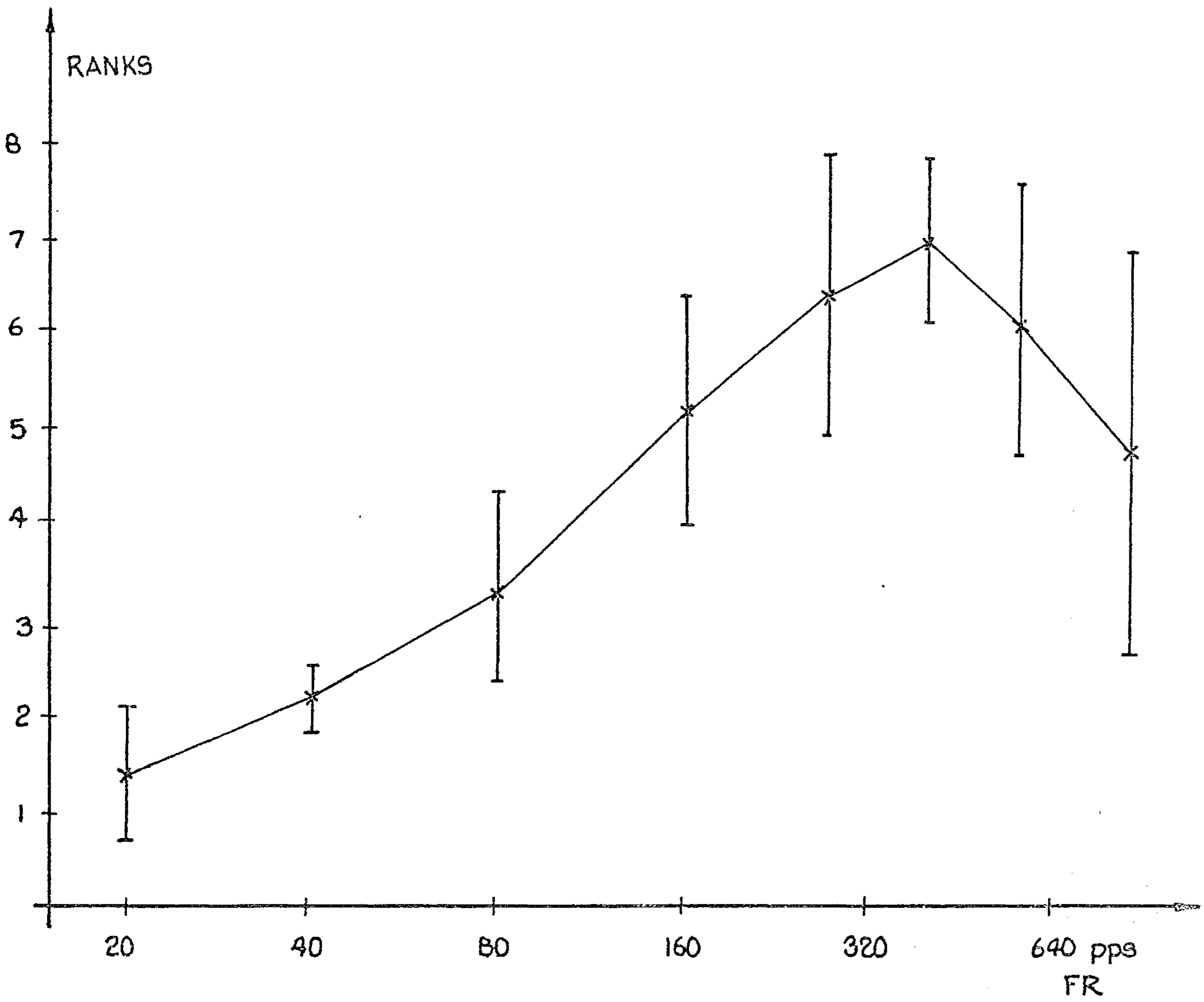
In comparing the equal loudness contours of periodic pulses in Fig. 6.8 and the pleasantness of periodic pulses in Fig. 1, it is noted that:

(a) the decline in the pleasantness of sounds above 400pps seems to correspond with a slower rate of decrease in loudness (i.e., an apparent increase in loudness)

Ferguson, G.A. (1971) Statistical analysis in psychology and eduction, 3rd edition, McGraw-Hill, N.Y., 333-335.

Subjects \ FR	20	40	80	160	280	400	560	800pps
IK	1	2	3	4	5	7.5	7.5	6
ML	1	2	3	5	4	7	7	7
RD	1	2	3	7	8	5.5	4	5.5
DMA	2	3	5	6	8	7	4	1
AC	1	2.5	4	7	5.5	8	5.5	2.5
LK	1	2	3	4	7	6	8	5
ES	1	2	3	4	5	6.5	6.5	8
RL	1	2	3	6	7.5	7.5	5	4
JB	3	2	1	4	8	6	7	5
LK	1	2	4.5	4.5	6	8	7	3
R_i	13	21.5	32.5	51.5	64	69	61.5	47
M_i	1.3	2.15	3.25	5.15	6.4	6.9	6.15	4.7
$SD_i(n-1)$	0.67	0.34	1.09	1.25	1.49	0.88	1.43	2.12

Table 1: Ranks of the Periodic Pulses Pleasantness Marks



PLEASANTNESS OF THE PERIODIC PULSES.

FIG. 1

of the equal loudness contour. (2 dB/octave for FR > 400pps c.f. 3dB/octave for 20pps < FR < 400 pps).

(b) The relatively low marks given to the pleasantness of sounds at very low FR seem to correspond to an increase in loudness for sounds below 160pps.

Noting that the slower rate of decrease in loudness for FR > 400pps and the increase in loudness for FR < 160pps have not been adequately explained in terms of their frequency components and their critical bands. It seems that, where an increase in loudness cannot be explained by the critical band theory, the pleasantness of the sounds is at its low level. This tends to suggest that the pleasantness of the sounds was exerting some influences on the judgement on loudness. It is possible that subjects might tend to reduce the sound level to reduce the annoyance of unpleasant sounds i their judgements on loudness, and therefore produce an apparent increase in loudness in the equal loudness contours. The rather smooth equal loudness contours, i.e., no sharp transition of the curve slopes, would suggest that the influences exerted by the number of excited critical bands and the sound pleasantness are intermixed in the subjects' judgement on the loudness of periodic pulses.

L. Kay, S. T. Bui, J. A. Brabyn, and E. R. Strelow, "Single object sensor: a simplified binaural mobility aid," *Visual Impairment and Blindness*, vol. 71, pp. 210-3, May 1977.